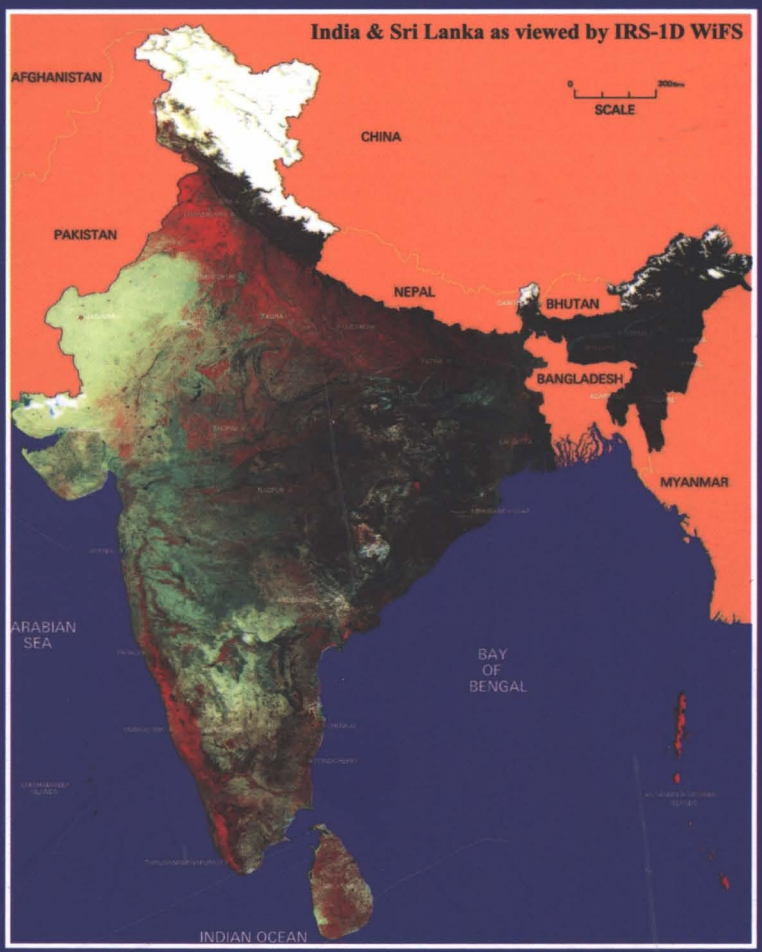
VOLUME 2

Geology of India

R. Vaidyanadhan
M. Ramakrishnan



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GEOLOGY
OF
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Volume 2

R. VAIDYANADHAN
and
M. RAMAKRISHNAN

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Foreword

A phenomenal growth has been achieved in our understanding of the Geology of India since India's Independence through the efforts of the Geological Survey of India and several other State Surveys, exploration agencies, research organizations, universities, institutes and scientific societies. Many of our earlier concepts of geology in relation to structure and tectonics, stratigraphy and sedimentation, magmatism and metamorphism, and metallogeny and mineral deposits have undergone drastic changes with larger inflow of data, synchronising with the evolving global concepts of earth processes. New dimensions have been added to Indian stratigraphy by detailed geological mapping on the one hand and through geochronology and to a limited extent geophysics and geochemistry. The need for a comprehensive, nevertheless succinct account of the geology of India, keeping in view the above developments, has been keenly felt and a positive step has been taken by the Geological Society of India in entrusting to two of our outstanding earth scientists, Prof. R. Vaidyanadhan and Dr. M. Ramakrishnan, the task of addressing this need. Professor Vaidyanadhan hails from an educational stream from the Andhra University and is widely known for his expertise in geomorphology and a capability for incisive synthesis and review. Dr. M. Ramakrishnan has several decades of dedicated field work in different parts of the country to his credit under the banner of the Geological Survey of India and in guiding streams of younger scientists in geological mapping and interpretation. Both the authors have published widely quoted papers of lasting value. They served the Geological Society in the challenging task of being successive editors to the Journal of the Society and have established editorial capabilities. It goes to the credit of these two earth scientists that they, in the present two volumes, provide an exhaustive and commendable synthesis of Indian geology, covering the major recent advances. They have thereby generated, perhaps, the almost up-to-date and authentic publication on the subject now available.

The authors have taken to a central path in areas of modeling diversity. Most evolutionary models find a mention in the text. Areas of geophysics and geochemistry are emphasized, but the main focus is on structure, tectonics, stratigraphy and the geological milieu. Though the Global Stratigraphic Scale is broadly followed, formations are described keeping in view their spatial and temporal continuity. Such a presentation has the merit of ensuring a wholesome picture of the geological history behind each of these geological entities which will be lost when mutilated into the various systems in the International Time Scale. Thus the Precambrian is described in terms of cratons, mobile belts and Proterozoic platformal sediments. Precambrian stratigraphy is well integrated with petrology and chemistry. In the Phanerozoic, considerable emphasis is laid on sequence stratigraphy in different regions and life (mega and micro) preserved in fossils during different periods. The Gondwana and the Siwalik sequences are described as single entities. The write-up on the Deccan and Rajmahal volcanism emphasises the several manifestations of the riftogenic episodes of continental volcanism, their chemical stratigraphy, petrology and petrogenesis. The Precambrian of the Himalaya is described in a chapter along with other Mobile Belts in Volume 1 and the Phanerozoic of the Himalaya in the successive chapters on Palaeozoic, Mesozoic and the Cenozoic in Volume 2. Offshore basins constitute the penultimate chapter. Geomorphic evolution is appropriately reserved to the end of the book as the last chapter. The book presents a selected bibliography that lists most of the significant contributions. The authors are constrained to be brief in several sections due to limitations of space.

I have been fortunate to be associated with the reviewing of several chapters at one stage or other and the final manuscript volume recently. I deem it a privilege to be requested by the Geological Society of India to write this Foreword to this book. A comprehensive treatise, the book would prove to be an up-to-date source of information on Indian continental geology. I recommend it for wide readership.

T. M. MAHADEVAN

Preface to Reprint Edition

There was an overwhelming response from the earth scientists to this book and all copies are sold out already. In view of this great demand, the Geological Society of India has decided to reprint the book with minimal additions/alterations so that there is no change in pagination. We have fulfilled this mandate by taking into account the suggestions from experts like O.N. Bhargava, L.S. Chamyal, G. Lakshminarayana, U.B. Mathur, A.C. Nanda, G.V.R.K. Prasad, K.N. Prudhvi Raju, D.S.N. Raju and Vishwas S. Kale. Major changes added here synoptically pertain to the Pandyan and Eastern Ghats mobile belts in Chapter 4 and 'Purana' basins in Chapter 5. The new International Stratigraphic Chart or ISC (ICS, 2009) printed in this reprint replaces the ISC 2004 included in the 2008 Edition of the book. Elsewhere, a table each has been added as folder in Chapters 6 (Palaeozoic) and 8 (Mesozoic), contents in a few tables substantially modified in Chapters 10 (Cenozoic) and 12 (Offshore basins), and ages changed in a few places based on geochronological and faunal evidence.

New plate tectonics signatures such as ophiolites, eclogites and high P-T metamorphism in the Eastern Ghats and Pandyan mobile belts have been described recently and linked to global supercontinent dispersal and assembly. The time span of 'Purana' basins has been revised to Mesoproterozoic (1000 to 1600 Ma) on the basis of isotopic ages of the upper sequences at ~1000 Ma (e.g. Bhander, Bhima / Kurnool, Chhattisgarh etc.) negating the earlier views of their Neoproterozoic (~500 Ma) age.

A Supplementary Bibliography has been added at the end of each volume to reflect the rapid changes happening in the geology of India. We have by and large laid emphasis on stratigraphy while making these

changes. The recent book "The Making of India – A Geodynamic Evolution" by K.S. Valdiya (2010), published by Macmillan (816p), is a valuable companion that deals with the geology of Himalaya and neighbouring regions (Pakistan, Tibet, Nepal, Bhutan, Myanmar, Sri Lanka and the Indian Ocean) in greater detail, covers broadly the Phanerozoic geology of India and contains an exhaustive list of references. Another recent book "Cratons and Fold Belts of India" by R.S.Sharma (2009) published by Springer (304p) is a useful supplement that compares and contrasts different evolutionary models, starting with an introduction to Precambrian terrains and tectonics.

We are grateful to the MSPL Limited, Hospet for liberal financial assistance for printing of this book.

The series of Memoirs released by the Geological Society of India in connection with the Golden Jubilee Celebrations in 2008 that highlight the advances made in different fields of the earth sciences in India are valuable sources of reference. These developments reflect the burgeoning progress of research and we could only provide a glimpse of it given the time and space constraints. We thank the Geological Society of India for its pro-active role.

31st May 2010

R.VAIDYANADHAN
M.RAMAKRISHNAN

Preface

Geology came to occupy the pride of place in the country following Independence and rapid industrialization based on Five Year Plans of the Nehru era. Geological Survey of India, the premier earth science organization in the country, was considerably expanded and decentralized to the various States of India. National Research Institutes like the NGRI, PRL, CESS, WIHG, BSIP etc. were encouraged to develop rapidly, and the Universities urged to become centers of excellence. The net result of the combined activity was the production of wealth of new data, forming the backbone for industrial advancement. The dissemination of new information was originally confined to specialist publications of limited circulation. The classical textbooks by D.N. Wadia and M.S. Krishnan, which met the requirements until the seventies, were fast becoming obsolete. The few books that appeared later had limited size and scope, and did not meet the popular demand. E.H. Pascoe's Manual in four volumes as well as the Revised Fourth Edition of the Manual of Geology of India by GSI are too big for general use. Specialized publications on the Precambrian of India and on the Indian plate as a whole mainly catered to specific sections of the geological community. The need for a textbook suitable for teaching, research and search for economic minerals was sorely felt soon. The present volume containing the collated and condensed data is designed to meet these needs. Its target readership is not only students, but also research scholars and professional scientists. The Geological Society of India, which pioneered the publication of textbooks on the States of India, has taken the lead to publish this volume also.

Classical geology is firmly rooted in stratigraphy, in conjunction with structural geology in deformed terrains. Stratigraphy is fundamental for building models of metamorphism, tectonics and crustal evolution, and is therefore the prime focus of this book. The scheme follows the recent (2004) International Stratigraphic Scale. The Code of Stratigraphic

Nomenclature is not rigorously adopted in India, and therefore some deviations are noticed in the correlation tables reproduced here from authors, who worked in different terrains in different periods. In some cases the names of the stages given earlier are different from those in vogue now. The most popular and widely quoted stratigraphic schemes are used in the book to maintain an even balance. The geology of India is a rich tapestry of geological history from the Archaean to the present day, of which the Himalaya as a classical example of continental collision, the Deccan Volcanic Province as an important Large Igneous Province of global importance, the 'Purana' Basins, a variety of greenstone belts and the typical granulite terrain forming the type area of charnockites have been the recent focus of international attention. In order to do reasonable justice to its complex geology and flood of new data, the book is organized into two volumes, broadly dealing with the Precambrian (Volume 1) and the Phanerozoic (Volume 2). R. Vaidyanadhan has written the Chapter 1 and the Phanerozoic part of Chapter 2 in Volume 1; and the Inter-trappean part of Chapter 9, and the Chapters 6, 7, 8, 10, 11, 12 and 13 in Volume 2. M. Ramakrishnan has written the Precambrian part of Chapter 2 and the Chapters 3, 4 and 5 in Volume 1; and the Deccan Trap part of Chapter 9 in Volume 2.

The Precambrian of India has been dealt with in terms of tectonic divisions like cratons, mobile belts and flat-lying cratonic basins. It is our belief that such genetic divisions are more durable than the ones based on geographical regions, chronostratigraphic schemes or those based on crustal evolution. The latter two criteria are subject to frequent change due to revolutionary changes in geochronology or the emergence of new paradigms like plate tectonics or its variant of plume tectonics. The core of the book has, however, the flexibility to accommodate any foreseeable new developments.

In the case of the Phanerozoic, the stratigraphy is presented in the conventional manner giving importance to sequence, lithology, life and broad correlation within each era. Gondwana and Siwalik are, however, dealt with separately since they occupy conspicuous special range in time and space in Indian stratigraphy with overlaps in time when

compared with the standard International Stratigraphic Scale (Gondwana from part of Palaeozoic to Mesozoic era and Siwalik from Miocene to Pleistocene epochs within the Cenozoic era). A brief presentation is made from the voluminous data published by ONGC on Offshore basins over the past half-a-century. Morphology and evolution of sections of Indian subcontinent come at the end to complete the story of the geology of India.

The Selected Bibliography at the end is not exhaustive and is largely limited to reviews or overviews, and to some of the recent ones that make any specific new viewpoint or present new data. Any omission in this regard is not intentional. Similarly, the references are not cited in the text at frequent intervals in order that the flow of the narrative is least interrupted. A substantial part of the text is drawn from the textbooks and memoirs of the Geological Society of India, regular and Special Publications of the Geological Survey of India and Proceedings of Seminars, besides important articles from the national and international journals.

Geological Map of India on 1:5 M scale published by the Geological Survey of India (GSI) in 1993 is included in this book for reference. The 'Legend' in the map may not correspond with the scheme used in the book, but the geological units in the map will form a useful guide. For additional information, the geological, tectonic, geomorphological and other thematic maps on 1:2 M scale published by GSI may be consulted.

We are grateful to the Department of Science and Technology, Government of India, New Delhi for a generous grant for publication of the book.

Padmashree (Dr.) B.P. Radhakrishna is the main source of inspiration for this volume. Without his constant goading and monitoring, it would not have been possible to complete this book.

R. VAIDYANADHAN
M. RAMAKRISHNAN

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Padmashri B.P.Radhakrishna, the doyen of Indian geology, has been a great source of inspiration and constant guidance in our endeavour. We owe a deep debt of gratitude to Prof. T.M.Mahadevan, who perused the manuscript critically and patiently, and offered very valuable suggestions for improvement. His sound geophysical understanding of geological problems was a great asset to us in his incisive review. He is also thanked for the Foreword to this book. He and Dr.S.M.Naqvi of the National Geophysical Research Institute, Hyderabad, have made the final appraisal of the manuscript volume, on behalf of the Department of Science and Technology, Government of India. Almost all the chapters of the book have been reviewed by at least two experts in the respective fields and we are grateful to them for sparing their valuable time. The experts in the alphabetical order are: O.N. Bhargava, L.S.Chamyal, A. Govindan, Jai Krishna, A.K. Jain, Vishwas S. Kale, Vivek S. Kale, G. Lakshminarayana, A.C. Nanda, K.N.Prasad, D.S.N.Raju, K.N.Prudhvi Raju, G.N.Rao, P.K.Saraswati, S.V.Srikantia, K.V.Subbarao, S.K.Tandon, R.C.Tewari, S.Viswanathan (Hyderabad), S.Viswanathan (Mumbai) and P.L. Zutschi. K.V. Subbarao is particularly thanked for help with the illustrations and literature on Deccan Traps. It must be admitted, however, that due to constraints of space, some of the well-meaning suggestions of the experts could not be incorporated in the book.

A host of friends and well-wishers have been of valuable help in providing us with notes, reprints, manuscripts, drawings, photographs, imagery, fossil plates and photocopies. Among them mention may be made of the following persons in the alphabetical order: Abhinaba Roy K. Ayyasamy, S.Balakrishnan, P.K.Banerji, N.P. Bhatt, A. Bhattacharyya, T.K. Biswal, G.Ch. Chennaiah, R.K. Ganjoo, N.C. Ghose, H.K. Gupta, M. Hanuma Prasad, A.K. Jaitley, M. Jayananda, V.K. Jha, G. Lakshminarayana, C.Leelanandam, Y.V.N. Krishnamurthy, S. Madabhushi, Mahadev, U.B. Mallikarjuna, R.K.Mazari, N.C. Mehrotra, K.S. Misra,

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We are thankful to Mahaveer and Siddu Kalagudi of MSPL Ltd. (Baldota), Bangalore, R.H. Rajiv of Geomysore Services, Bangalore, and Naga Murari and Madan Mohan of Mumbai for digitization of some figures. We are thankful to R.H. Sawkar, V.N. Vasudev and K.V. Subbarao for coordinating the digitization of some figures. M.Nagaraju of Driti Enterprises, Bangalore is thanked for undertaking the task of printing and binding with customary zeal.

We are grateful to a host of publishing houses listed under "Permissions" in each volume and copyright holders who have generously granted us permissions to reproduce illustrations from various publications. The main sources are the Geological Society of India, Geological Survey of India, Elsevier Scientific Publishers, Current Science, Prof. A.B.Roy and Scientific Publishers (India), Jodhpur, and Gondwana Geological Society, Nagpur. Many other sources, which have enriched the book, are listed under Permissions.

We are grateful to the Geological Society of India, Bangalore for acceding to our request for publication of the book. B.P. Radhakrishna, H.K. Gupta, M.S. Rao and R.H. Sawkar have evinced keen interest in speedy publication. The following staff of the Geological Society of India are thanked for their prompt help in many ways in the preparation of the book: Subhash Chandra, Jitendra Kumar, S. Shivanna, Nagabhushana, Venkataramaiah, Dharmaraju, Meera, Nalini, Veena, Govindaraju and Seetharamiah.

The authors would like to express their gratitude to their spouses Lakshmi Vaidyanadhan and Saroja Ramakrishnan and their sons Sridhar and Ravi Vaidyanadhan and Anand and Kartik Ramakrishnan and their families, who have been a great source of strength during the trying times on this seemingly endless journey towards our goal, spanning many years. M.Ramakrishnan offers his obeisance to Agastya Mahamuni, Lopamudra Devi and Pradhanacharya of Gnana Kendra (A.N.Shankar) in Bangalore for their blessings in this project.

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R. VAIDYANADHAN
M. RAMAKRISHNAN

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6

Palaeozoic

INTRODUCTION

Rocks of the Palaeozoic era covering a span of about 290 Ma occur mainly in the Himalayan region and that too most of them in the Tethyan basin, extending from Kashmir in the northwest to Bhutan in the east (Fig.6.1). A detailed study of the stratigraphy and structure of the formations in these basins has been made for over a century and the lithological and chronostratigraphic correlation of Palaeozoic sequences of the Higher Himalayan Tethyan belt are well established. The conspicuous features in this are the hiatuses at Late Cambrian, Late Carboniferous and Middle Permian. Some Early Cambrian strata are reported to be present in Peninsular India as well.

In the early days, the stratigraphy of the Himalayan terrain was worked out mainly based on the observations made during traverses along the river sections across the mountain ranges. Among others Greisbach, Middlemiss, Hayden, Heim and Gansser, and Wadia contributed to the geology of different areas in the Himalayan terrain, while Stoliczka and Reed contributed to our knowledge of the fossils of the Palaeozoic. Later, attempts were made to correlate the different horizons named after local places along these sections. However, during the last few decades, traverses were made (aided by aerial photographs) along the strike of the formations as well and detailed lithological mapping was done after recognizing marker beds. This necessitated change in nomenclature and a need to conform as far as possible to the Code of Stratigraphic Nomenclature of India (GSI, 1971). Still one comes across new names for formations of the same age and lithology in some parts of Himalaya and new classifications are emerging. This is partly due to (i) the nature of the terrain being not easily accessible, (ii) lack of habitations with names to be utilized for naming the formations and (iii) thickness of the formations not provided as required by the Code. Some of the designated formations, even if based on the find of some fossils in them, are not mappable. Therefore, only those classifications based on regional lithostratigraphical mapping have validity and

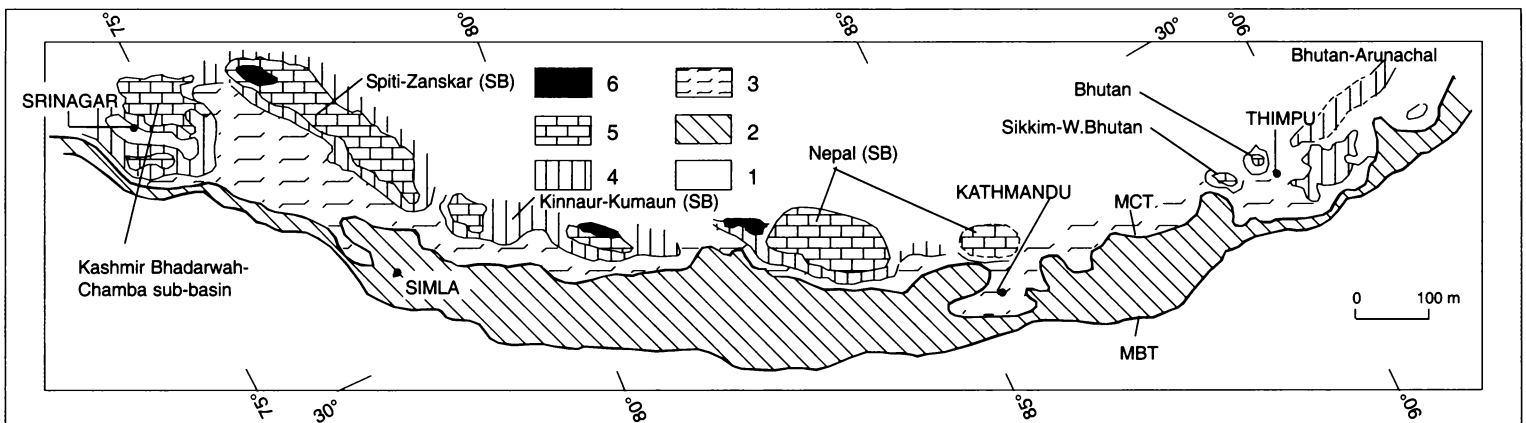


Fig.6.1. Tethyan Basins of the Himalaya. **1** - Tertiary; **2** - Lesser Himalayan Sequences; **3** - Crystalline Thrust Sheets; **4** - Eocambrian-Palaeozoic; **5** - Mesozoic; **6** - Ophiolite Nappe; **MCT** - Main Central Thrust; **MBT** - Main Boundary Thrust. (Courtesy: O.N. Bhargava).

are adopted. It may also be noted that there is an emerging attempt to refine the classifications in the final presentation of geology of regional belts in the Himalaya. This is naturally to be expected, as the areas get to be mapped on larger and larger scales by geologists with wider and longer experience. In the final analysis the facts gathered by rigorous fieldwork and regional mapping, provide the lead to our expanding knowledge.

TETHYAN BASIN

The term Tethyan basin, by long usage, has come to be applied to the thick Palaeozoic and younger sediments in the Himalayan domain, north of the Main Central Thrust and its analogues, extending from Kashmir in the NW to Arunachal Pradesh in the SE. The Kashmir, Bhadarwah-Chamba, Zanskar-Spiti-Kinnaur, Garhwal-Kumaun, Nepal-Sikkim-Bhutan-Arunachal Pradesh are the individual segments or sub-basins in the vast spread of the Tethyan basin (Fig. 6.1). Therefore these segments are referred to as sub-basins.

Kashmir Sub-basin

The Phanerozoic in the Tethys Himalayan basin of Kashmir (Fig.6.2) trends NW-SE and covers an area of about 18,000 km^2. It is separated from the Spiti–Zanskar sub-basin by the Kishtwar-Giambal-Nunkun-Suru crystalline zone. In the southwest, it is tectonically delimited by the Panjal thrust, along which the rocks have been transported over the Lower Himalayan tectogen. On the northeast, the Kashmir Tethyan belt overrides the Indus tectonic zone along the Sunko thrust. The Lidder valley forms a part of the southeast zone of the basin. It displays an excellent section of the Palaeozoic sequence of the Tethys Himalayan basin. The sequence earlier classified by Middlemiss, however, offers scope for revision in respect of lithostratigraphy and nomenclature (Table 6.1).

In the Lidder Valley, the Palaeozoic rocks together with the Triassic sequence are folded as NW-plunging overturned anticline designated as Lidder Anticline, with its main closure located in Walorama sector (Fig.6.3).

South of the Panjal thrust is the "Autochthonous Zone" representing a folded and imbricated belt. This extends from Uri in the Jhelum valley in the west to Chauhra in the Ravi valley in the east, into the Jammu and Kashmir (J & K), and further east links up with the Shali structural belt of Lesser Himalayan tectogen of Himachal Pradesh. This is bound to the south by the Murree Thrust, separating it from the Tertiary rocks, mainly Murree and Siwalik Formations, whereas the Panjal Thrust marks its northern limit with the 'Nappe Zone' made up of older rocks forming the basement of the Tethyan sediments.

The Panjal thrust is a high angle major tectonic lineament dipping towards north and is traceable from Jhelum valley to Ravi valley in the east and beyond into the Satlej valley in Himachal Pradesh. The tectonic plane, considered earlier to be the trace of 'Panjal Thrust' in the Chenab valley, is found to be a major fault - the Sudh Mahadev Fault - within the Autochthonous Fold Belt.

Bhadarwah-Chamba Sub-basin

This lies to the southeast of the main Kashmir sub-basin. It exposes the Permo-Triassic sediments overlying the Panjal volcanics, which unconformably overlie the Precambrian-Eocambrian rocks.

The Outer and Lesser Himalaya can be divided into the tectonic units from south to north as shown below.

Tectonic setting of Lesser Himalaya of Jammu (modified after Shah, 1980, p.153)

South	Outer Siwalik Belt
	— — — — — — — — Jammu Fault — — — — — — — — — —
	Murree Belt, with Jammu Limestone capped by Eocene (Subathu facies) in basement high regions and Siwalik rocks in the synclinal areas
	— — — — — — — — Murree Thrust — — — — — — — — —
	"Paraautochthonous" zone containing Shali Formation, Mandi Trap, Agglomeratic Slate and Eocene (Hazara facies) showing a younging of succession westwards
	— — — — — — — — Panjal Thrust — — — — — — — — — —
North	Kashmir Synclinorium, with the southern limb bearing rocks of the mixed Tethyan and "Lesser Himalayan" affinities

Spiti-Zanskar and Kinnaur Sub-basins

The Palaeozoic and Mesozoic sequences in the south Ladakh of J&K and Spiti and Kinnaur area of Himachal occur in two isolated synclinoria having comparable lithostratigraphic and faunal contents. They possibly represent part of the same basin, now separated due to erosion along a structural high. The Kinnaur sub-basin links up with the Garhwal-Kumaun Tethyan sub-basin of Uttarakhand across south Tibet. These segments together constitute the Spiti-Zanskar basin in the Indus Himalaya, exposing a spectacular, almost uninterrupted Proterozoic-Palaeozoic-Mesozoic–Tertiary succession in the Indian Himalaya (Figs. 6.4 and 6.5). It is bound by the Vaikrita Group of Central Crystalline Zone on the southwest side and by the Indus Tectonic Zone on the northeastern side. The geology of this region has been worked out in considerable detail and a part of the geological map of this region together

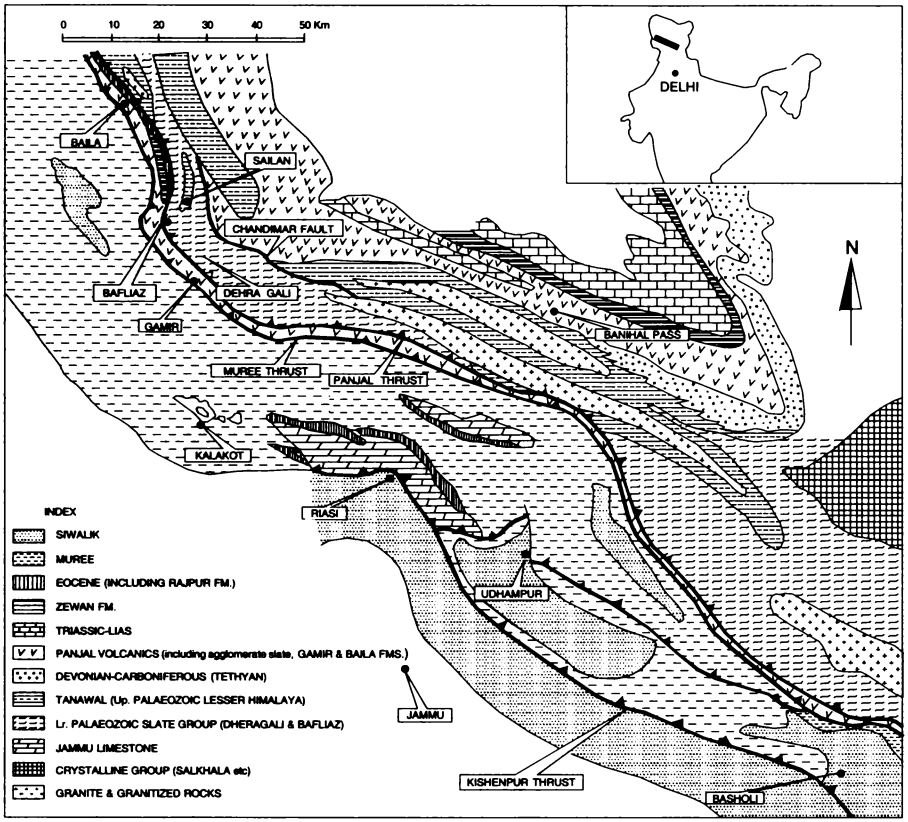


Fig.6.2. Geological sketch map of the Kashmir Himalaya showing various tectonic and stratigraphic units (after Shah, 1980; reprinted with permission from Hindustan Publishing Corporation, New Delhi).

with a section is presented in Figs.6.4a and 6.4b. The overall stratigraphic sequence is shown in Fig.6.5.

Garhwal-Kumaun Tethyan Sub-basin

The Garhwal-Kumaun Tethyan sub-basin is mainly seen in the Malla Johar and northern Kumaun areas. This zone comprises a thick sequence of sedimentary rocks of Proterozoic-Phanerozoic formations.

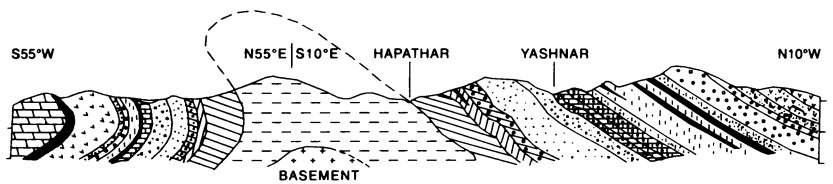


Fig.6.3. Geological cross-section across Lidder Anticline in Walorama sector, Kashmir (after Srikantia and Bhargava, 1983, p.374).

Table 6.1. Lithostratigraphic classification of the Palaeozoic sequence of the Kashmir Tethys Himalayan sequence in the Lidder Valley, Jammu and Kashmir (modified after Srikantia and Bhargava, 1983)

Age	Group	Formation	Thickness (m)	Middlemiss (1910)
Triassic	Sonamarg			
Upper Permian	Panjal Volcanics	Zewan upper lava flows	2000	
Lower Permian		lower volcanogenic association	250	
Lowermost Permian to Carboniferous	Lidder	Pindobal	700	Agglomeratic slate
		Ganeshpur	1800	Fenestella Shale
		Aishmuqam	700	Passage Beds Syringothyris Lst.
Devonian	Chorgali	Wazura	500	
		Muth	1000	Muth Quartzite
Cambrian to Middle Silurian	Hapatnar	Rishkobal	500	
		Rangamal	400	
		Shumahal	3500	
		Base not exposed		

Though almost close to each other, the thickness of the various stratigraphic horizons in the adjoining basins across the Himalaya differ considerably from Kashmir in the northwest through Spiti-Zanskar in Himachal Pradesh and Uttarakhand and at the other end in Nepal-Bhutan and Arunachal Pradesh. Detailed descriptions of these formations follow under different periods of the Palaeozoic.

PALAEOZOIC LIFE

Invertebrates

Early life seems to have been essentially marine and practically most of the invertebrate fauna known now, existed in some part or other of the Palaeozoic. Unicellular organisms were quite common. Foraminifera (Protozoa) were present right from the Cambrian times though they assumed some importance in the Carboniferous. Sponges (Porifera), one of the simplest multicellular organisms and essentially marine, increased in number only in the Carboniferous. However, there are not many reports of sponges from India. Corals came into prominence in Ordovician and Silurian and continued in other

succeeding eras as well. They are among the main carbonate builders. The exclusively marine echinoderms, which persisted almost through the entire geological column of the Phanerozoic, were mostly represented by cystoids in the Palaeozoic right from Cambrian, becoming prominent in Ordovician-Silurian and became extinct by Permian. Blastoids were also mainly confined to the Palaeozoic. Crinoids were more abundant in the Paleozoic era than the other echinoderms.

Bryozoans, which were dominantly marine in habit, generally are found as encrustations on foreign bodies like shells. These are seen occurring as colonies and are termed 'coralline crags' though they are not strictly corals in their structure. Though known to have appeared in Ordovician, a majority of them are known in India from the Permian only.

Brachiopods, which are exclusively bivalved species, are known to have one of the longest ranges of existence among the invertebrates right from Cambrian to Tertiary. Even in India, *Lingulella*, *Obolus wastonia* and *Obolella atlantica* have been reported from the Cambrian of Spiti. Since most of them are made up of calcareous matter, they are very well preserved and hence are in a position to be used in stratigraphic classification. Within the Palaeozoic, their occurrence in the Permo-Carboniferous strata of Kashmir and Spiti is well known and so also in the Salt Range in neighbouring Pakistan, productids being the most important.

Mollusca perhaps represent one of the largest groups of invertebrate fossils that have worldwide distribution. Pelecypods, also known as Lamellibranchiata, live in fresh, brackish and marine waters. These also range in time from Cambrian to Holocene. Except in a very few cases, these cannot be considered as constituting important zone fossils in the Palaeozoic. The gastropods can thrive in all types of environments from the waters of great depths in the oceans (5000 m) to over the tops of the mountains in the lakes of Himalaya (6000 m). They do appear in Cambrian, are represented by a few species in Ordovician-Silurian and occur in considerable numbers in the Permian. Cephalopods, which are exclusively marine, are represented by a few species in the Ordovician and a few more in the Permian.

Ostracodes are known from the Palaeozoic. However, the fossils that are of considerable importance as index fossils in the Lower Palaeozoic are trilobites, which became almost extinct by the end of Permian. Conodonts were described and illustrated about 150 years ago. Their lack of facies restriction and worldwide distribution has helped in their use for correlation. They extend from Cambrian to Triassic. They are reported from some of the Palaeozoic strata in the Himalaya. Graptolites do not seem to have made their presence in India. In Plates 6.1 to 6.3 are presented some of the important fossils of the Palaeozoic era from the Himalayan terrain.

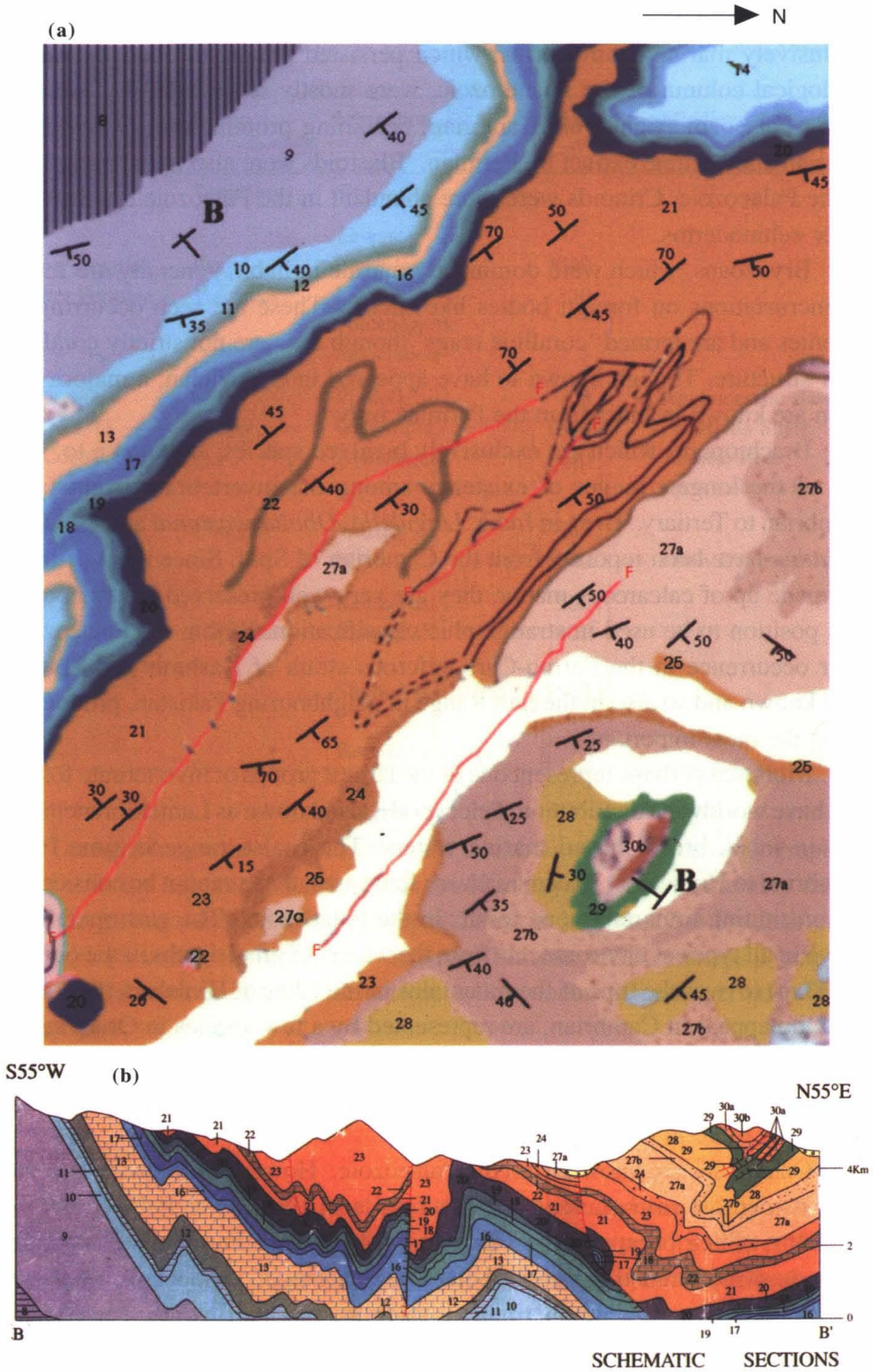


Fig.6.4. Geological map (a) and section (b) of part of Spiti-Kinnaur area, Himachal Pradesh (after Bhargava and Bassi, 1999). (see Fig.6.5 for explanation of the numbers in the map and the section)

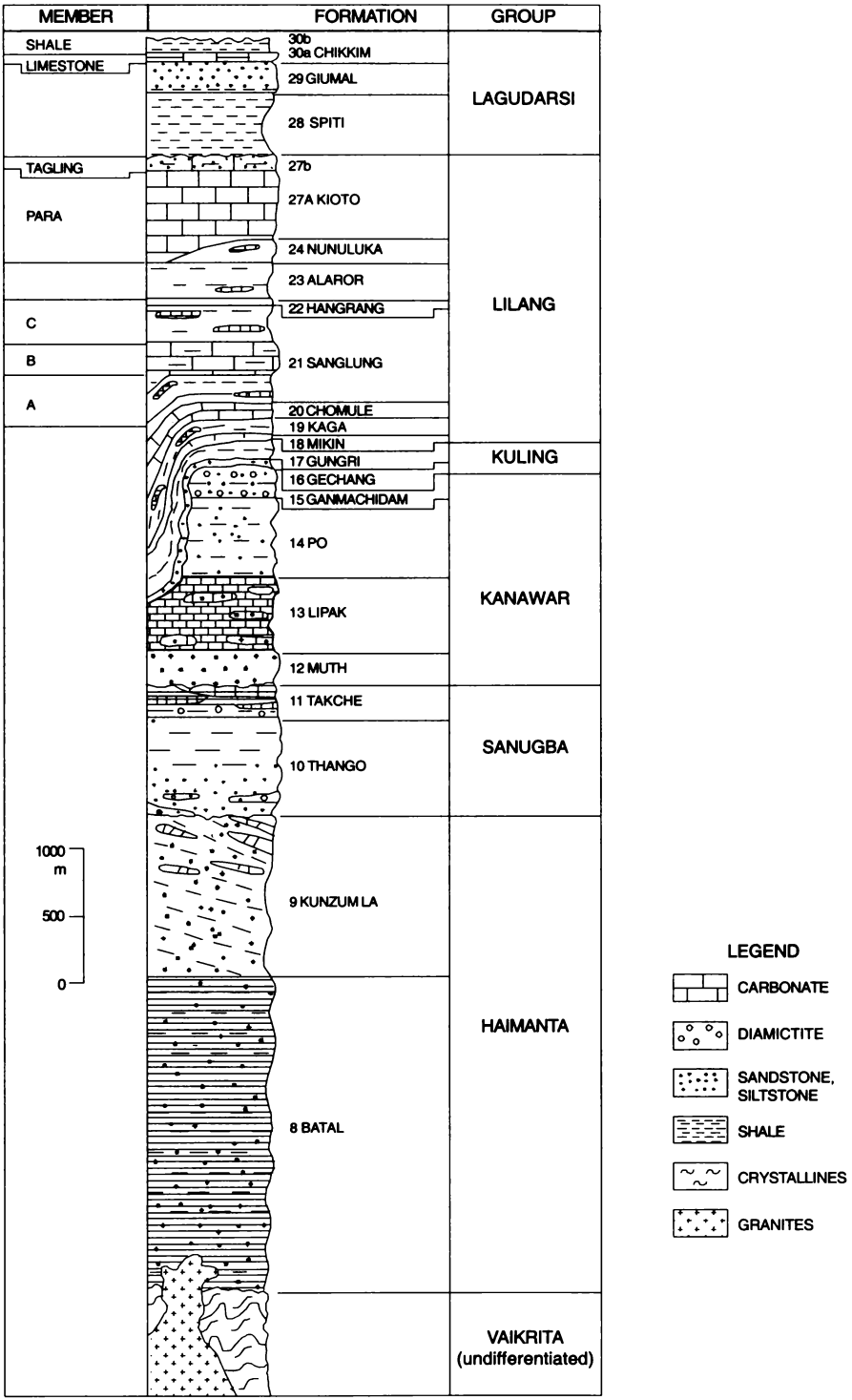


Fig.6.5. Litholog of the Tethyan sequence, Spiti-Kinnaur area, Himachal Pradesh (after Bhargava and Bassi, 1999).

Vertebrates

Perhaps it is in the Devonian that primitive vertebrates came into being. Amphibians perhaps evolved from the fishes of the earlier Silurian period and made their presence.

Plant Life

Acritarcha are unicellular microphytoplankton of organic composition of an unknown life cycle. They are mainly marine in nature and occur in rocks ranging in age from Precambrian to the Recent. They attain their acme period during Ordovician-Devonian time. At present, it is believed that most acritarcha are derived from either unicellular green algae, dinoflagellates or from precursor organisms in the evolutionary lineage of dinoflagellates. Algae are known from even the Precambrian strata in India. Vascular plants came up in the Cambrian. An advance in the plant life can be seen in Devonian with Charophyta and Algites, and there were quite a few representatives of the plant kingdom. It was in the Carboniferous that luxuriant vegetation thrived in other parts of the world (ultimately giving rise to extensive coal seams), but with only a few representatives in the Himalayan region. It was, however, in Peninsular India that we come across plants belonging to many families in the Gondwana strata of Permian. The discovery of plant-bearing beds from the Lower Carboniferous sequence of Kashmir region has opened up a new field of palaeobotanical study involving Carboniferous or Pre-Gondwana flora in Kashmir. The earlier knowledge of Pre-Gondwana flora in the Indian subcontinent was negligible and restricted to Spiti in Himachal Pradesh.

Six horizons (Table 6.2) have been recognised at distinct stratigraphic levels, out of which four show presence of Pre-Gondwana or Devonian-Carboniferous flora and two Permian floras. The latter are somewhat similar to the Lower Gondwana flora of Peninsular India. In the Upper Devonian the plant fossils are extremely rare and very badly preserved. The Lower Carboniferous flora show a remarkable resemblance with those known from the Lower Carboniferous flora from other parts of the world.

MAGMATIC ACTIVITY

There was invasion of granitic magma on a large scale throughout the Himalayan province from Manshera in northern Pakistan to Manaslu in Nepal and beyond. The climax of this granitic activity occurred 525 to 475 Ma ago. This seems to have affected the older Proterozoic rocks, which it invaded, causing low grade metamorphism of those sediments.

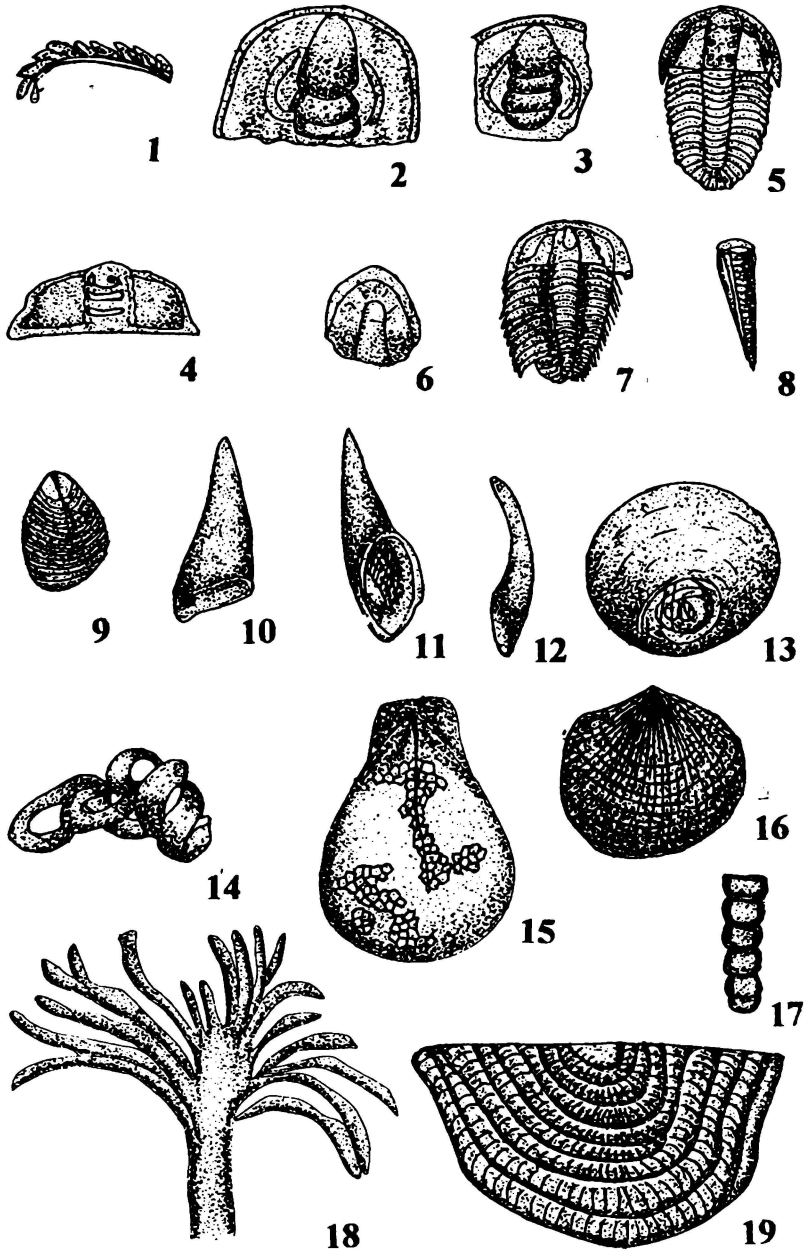


Plate 6.1. 1. *Phycodes pedum* (Early Cambrian); **2.** *Redlichia noetlingi* (Early Cambrian); **3.** *Redlichia noetlingi* (Early Cambrian); **4.** *Oryctocephalus indicus* (Early-Middle Cambrian); **5.** *Oryctocephalus salteri* (Late Middle Cambrian); **6.** *Diplagnostus planicauda* (Late Middle Cambrian); **7.** *Damesops sheridanorum* (Late Middle Cambrian); **8.** *Hyolithes* (*Orthotheca*) aff. *plicatus* (Early Cambrian); **9.** *Lingulella spitiensis* (Early Cambrian); **10-11.** *Maldeotaia bandalica* (Early Cambrian); **12.** *Protohertzina anabarica* (Early Cambrian); **13.** *Olivooides multisulcatus* (Early Cambrian); **14.** *Spirellus shankeri* (Early Cambrian); **15.** *Apiduim indicum* (Late Ordovician); **16.** *Orthis* aff. *spitiensis* (Silurian); **17.** *Orthoceras commutatum* (Ordovician); **18.** *Phycodes circinatum* (Early Ordovician); **19.** *Leptaena trachealis* (Ordovician). (Courtesy: O.N. Bhargava).

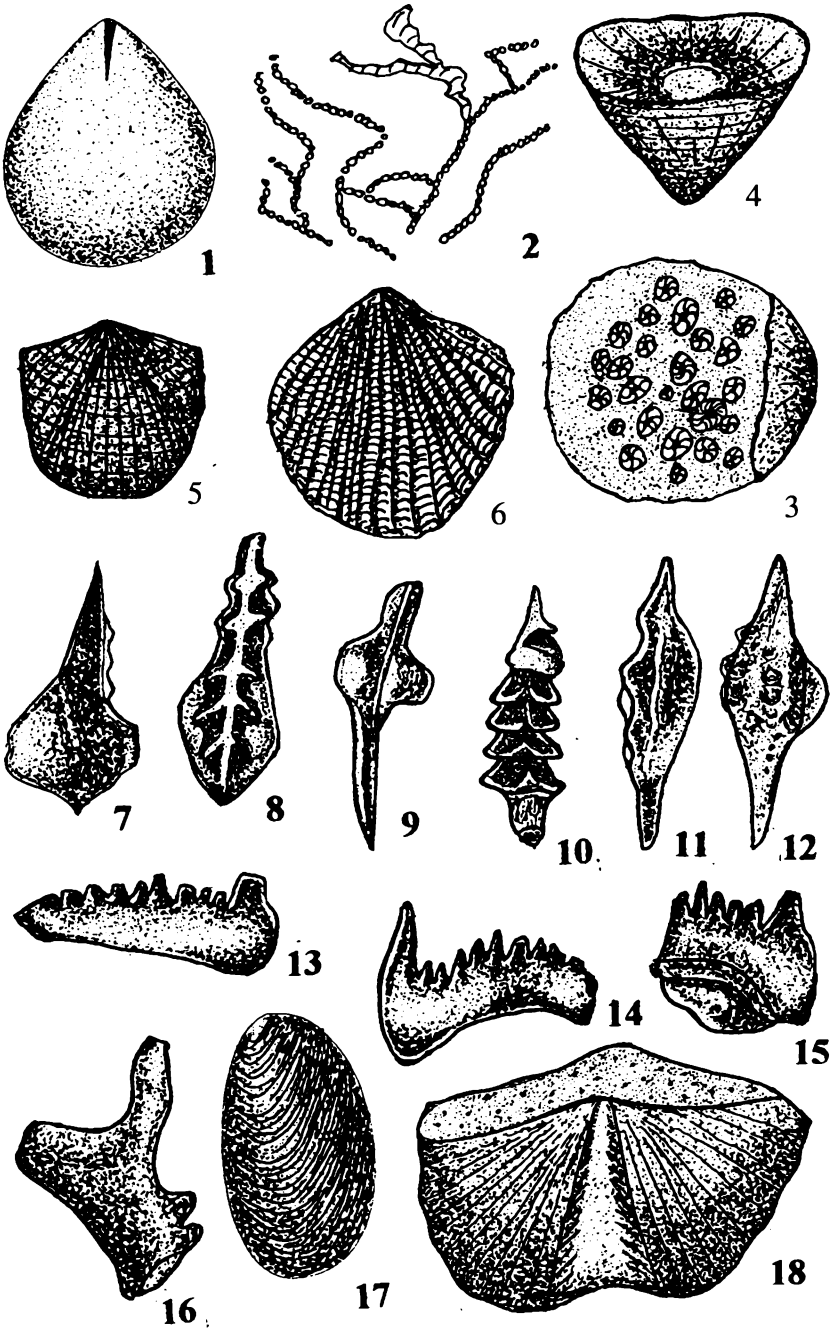


Plate 6.2. 1. *Pentamerus oblongus* (Silurian); **2.** *Halysities catenularia* var. *kanurensis* (Silurian); **3.** *Radiastraea* sp. (Silurian); **4.** *Calceola sandalina* (Devonian); **5.** *Atrypa reticularis* (Silurian); **6.** *Atrypa* aff. *spinosa* (Silurian); **7-8.** *Icriodus difficilis* (Devonian); **9-10.** *Icriodus arkonensis* (Devonian); **11-12.** *Pseudopolygnatnus primus* (Devonican); **13.** *Bispathodus aculeatus anteposicordus* (Devonian); **14.** *Bispathodus aculeatus plumulus* (Devonian); **15.** *? Hindeodus cristulus (Devonian)*; **16.** *Clydagnatus cavusformis* (Devonian); **17.** *Modiola liderensis* (Early Carboniferous); **18.** *Syringothyris cuspidata* (Early Carboniferous). (Courtesy: O.N. Bhargava).

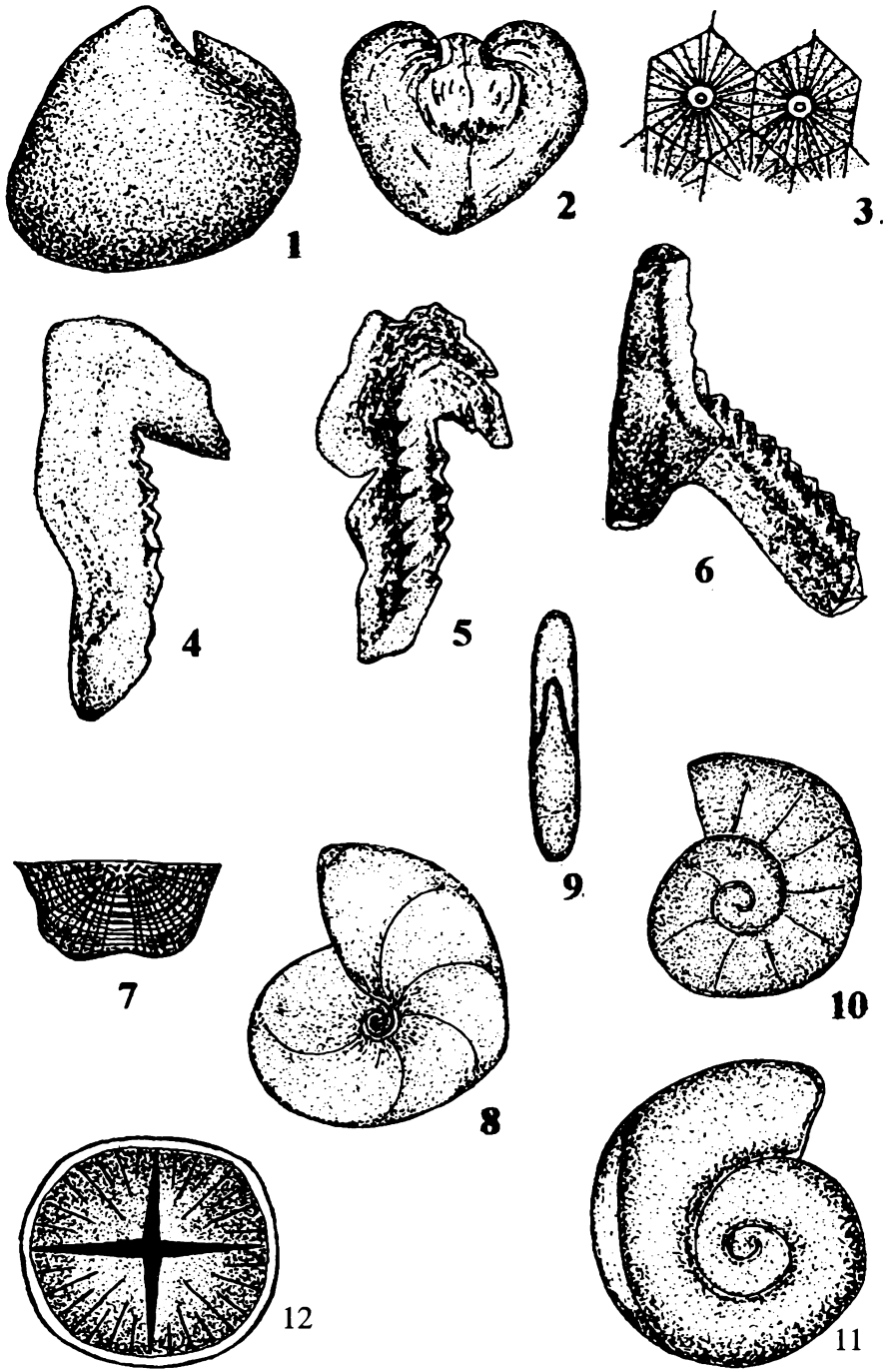


Plate 6.3. 1-2. *Eurydesma cordatum* (Early Permian); **3.** *Lonsdaleia salinaria* (Permian); **4.** *Clydagnathus unicornis* (Early Carboniferous); **5.** *Clydagnathus gilwernensis* (Early Carboniferous); **6.** *Neoprioniodus confluence* (Early Carboniferous); **7.** *Lamnimargus himalayaensis* (Late Permian); **8-9.** *Cyclolobus oldhami* (Late Permian); **10.** *Xenodiscus carbonarius* (Late Permian); **11.** *Xenaspis carbonaria* (Late Permian); **12.** *Zaphrentis beyrichi* (Late Permian). (Courtesy: O.N. Bhargava).

Table 6.2. Upper Palaeozoic succession in Kashmir showing plant-bearing horizons

Age		Stratigraphic Unit		Main Lithology
		Formation	Member	
Permian	Upper	Zewan	D	Calcareous sandstone with bands of limestone
			C	Arenaceous and calcareous shale
			B	Limestone shale intercalation
			A	Massive limestone with shale partings
		/////// Mamal //////		Novaculite, limestone, tuffaceous shale Carbonaceous shale, purple and pinkish shale with arenite
	Lower	Panjal Volcanics		Mainly basic rocks – basalt and andesitic basalt and a few intermediate and acidic rocks
		////// Nishatbagh //////		Black shale/slate, siltstone and bands of arenite
Carboniferous	Upper	Agglomeratic Slate	D	Ash colour tuffaceous shale with volcanic bombs, lapillae etc. Clasts rare
			C	Dominantly quartz-arenite with lenticular conglomerates and clasts
			B	Dominantly shale and siltstone with abundance of clasts
			A	Dominantly quartz-arenite with lenticular conglomerates and clasts
	Lower	Fenestella Shale	D	Dominant shale-siltstone with bands of quartz arenite
			//C//	Dominant quartz arenite with bands of shale and siltstone
			B	Dominant shale/siltstone with bands of arenite
			//A//	Dominant quartz-arenite with intercalation of shale siltstone
		Syringothyris Limestone	//C//	Limestone shale/siltstone/arenite intercalations
			B	Massive and thickly bedded limestone
			A	Limestone and arenite
Devonian	Upper	Wazura	//B//	Yellowish-green siltstone-shale with bands of quartz-arenite
			A	Quartz-arenite with intercalation of blotchy siltstone
Muth-quartzite				Milky white orthoquartzite

//////// indicates plant-bearing horizon (modified after Gopal Singh et al. 1982)

PRECAMBRIAN/CAMBRIAN BOUNDARY

Precambrian-Cambrian transition is marked by major biotic changes, viz. emergence of soft-bodied Ediacaran fauna and their subsequent extinction, emergence of fauna with hard parts or chemical changes, particularly variations in the C and Sr isotopic compositions of the carbonates. All of them provide significant stratigraphic information, which may be used for the correlation of Terminal Proterozoic and Early Cambrian strata. Nutrient enriched water masses (NEW) with high levels of dissolved phosphate and silica, with low levels of oxygen have left a clear imprint of the history of fossil records of the latest Proterozoic – Early Cambrian.

Study of ratio of ^{13}C and ^{12}C helps in deciding the organic or inorganic origin of the carbon in samples. Based on this study, strong evidence of life has been established on the earth even as early as 3850 Ma ago.

Explosion of life at pC/C boundary saw varieties of animals emerging as builders, binders and encrusters in various build-ups. Around 544 Ma ago during the Early Cambrian period, there was an evolutionary explosion, referred by palaeontologists as the Cambrian "Big Bang" which extended up to the middle of Ordovician (460 Ma). But some on the basis of nucliotide (an organic compound consisting of Purine and Pyrimidine base) sequence studies put the origin and diversification of the major phyla between 1000-2000 Ma. Lack of fossils may be due to preponderance of soft-bodied forms, and due to unsuitable fossilization conditions.

Trace Fossils

Trace (or Ichnofossil) fossil studies have begun to play an increasing role in understanding of the nature of early metazoan life and also as stratigraphic indicators particularly in the uppermost Precambrian–Cambrian sequences. The DNA studies had modelled the evolution to higher metazoans from simple forms thus: sponges to à diploblastic (2 germ layered forms like jelly fishes, sea anemones) to à triploblastic acoelomate forms to-à triploblastic coelomates having distinct three-layered bodies plan (arthropods, molluscs, annelids). The studies related to labenspurren (sedimentary structures left by a living organism) are of immense use in interpreting the palaeoenvironment.

Almost towards the end of the Precambrian, when 90% of geologic time was over, metazoans or the multicellular life forms began evolving around 600 Ma ago. This period was well marked by the enigmatic ediacaran fauna, whose precise age as well as origin, whether animals or plants, were matters of long controversy. The ediacaran fauna of soft -bodied metazoans was discovered in 1947 in Australia.

An examination of all the recent worldwide studies on ichnology (study of trace fossils, especially the study of fossil tracks) seems to result in the following generalised stratigraphic sequence from Proterozoic to Lower Palaeozoic.

L. Palaeozoic - (a) Rocks with trilobite, brachiopods, archaeocyathids and abundant trace fossils (at the top)
(b) Trilobites with other trace fossils
(c) Soft-bodied metazoans (Ediacaran and alike fauna)
Proterozoic - (d) Rare trace fossils with stromatolites (at the bottom) (Plate 2.1 in vol.1).

Traditionally, Lower Cambrian and Precambrian were placed at the levels (a) and (d) respectively. The transition was conceived at levels (b) and (c). The boundary was placed right below the lowest record of trilobite body fossils, though it is now being placed at the first appearance of trilobite traces.

The Late Precambrian (Vendian) traces are very simple horizontal burrows, trails and resting excavations *(Plagiogmus, Cochilichnus, Helmenthopsis, Astropolichnus)*. The base of the Cambrian (Tommotian) is marked by the sudden increase in diversity and density of traces owing to the development of phyla Annelida, Arthropoda and Mollusca.The beginning of the Tommotian is precisely indicated by the first appearance of trilobite traces and not trilobite body fossils. Most of the primitive trilobites are thought to have had soft bodies. Hard-bodied forms appeared somewhere in the Lower Cambrian. Thus, the first appearance of traces of trilobite origin such as *Cruziana, Diplichnites, Monomorphichnus, Dimorphichnus* and *Rusophycus*, besides a few non-trilobite traces, is considered to indicate the base of the Cambrian. Since the beginning of Cambrian is indicated by the first appearance of trilobites or arthropo-grade organisms, the base of the Cambrian is recommended to be placed below the oldest level of trilobite traces and not body fossils.

Both the Vendian and Tommotian successions with rich biota are developed in continuous sections in many parts of the world, especially in Russia, Mongolia, China, India, Pakistan, Canada and Australia.

Stromatolites

In India stromatolites are reported from Lower Proterozoic of Udaipur area and Upper Proterozic of Chittaurgarh and Bundi areas in Rajasthan; they are also known from rocks of Sandur, Shimoga and Chitaldurga belts extensively in Karnataka, dated around 2.9 b.y. Stromatolites are not "body fossils" but

traces of life activity. They are sedimentary structures built by bacteria, cyanophytus and microscopic algae, and only rarely do they contain remains of organisms that formed them. Yet, the biologically and environmentally informative shapes and fabrics of these microbial colonies are well recorded.

Stromatolites have also been recorded from Raisi Group of Jammu Himalaya, Himachal Himalaya: Larji/Shali/Deoban Groups, Garhwal-Kumaun Himalaya: Calczone of Pithorgarh, Nepal Himalaya and Sikkim-Bhutan-Arunachal: Buxa Group – Carbonate Formation.

In all reported occurrences of stromatolites, both in Peninsular India as well as in Himalaya, the stromatolites always belong to Precambrian sequences except in the Tal Formation in the Mussoorie Hills in Uttarakhand where the upper age limit may be Early Cambrian. Record of *Collumnaefacta vulgaris* is an important discovery, which also supports Lower Cambrian age to the Tal.

pC/C BOUNDARY IN HIMALAYAN BASINS

The sedimentation of the terminal Proterozoic-Cambrian succession commenced with a widespread marine transgression in what is now the northwestern Himalaya, in response to global warming after the Varangian glaciation about 610 to 590 Ma. Salkhala Group and part of Haimanta Group (Batal Formation) represented Neo- and Terminal Proterozoic in Lahaul-Spiti-Kinnaur in Himachal Himalaya. The transgression got terminated with Pan-African orogeny in late Upper Cambrian. These sediments are now exposed in the Krol belt, Lesser Himalaya, in Kashmir basin in Higher Himalaya, and Spiti-Zanskar and Kumaun basins (Fig.6.1). The sequence shows considerable variation in lithology due to variable conditions of depositional environment and climate. Though similar fossils belonging to different phyla, algae, and acritarchs occur in all the three basins, they do not necessarily occur in the same sequence, but a limited degree of contemporaneity is indicated which permits fixing tentatively the pC/C boundary in the three basins. Most Proterozoic and Cambrian acritarchs occur in all kinds of marine shelf deposits. The lowest record of trilobite is not necessarily at the commencement of Cambrian, but just at late Lower Cambrian with trace fossils *Treptichnus*, *Cruziana* and trilobite *Redlichia noetlengi* (Plate 6.1). Rapid evolution and diversification of biota leading to the appearance of hard parts or skeleton in animals is noticed above what is termed as the fourth depletion in $\delta^{13}C$ values, i.e. above the ediacaran fossiliferous horizon in the Blaini-Krol-Tal sequence in the Krol belt. Blaini-Krol-Tal sequence is considered by some as one of the standard Terminal pC/C sequences in global correlation. The Blaini-Krol-Tal (BKT) succession was believed for a long time to be Mesozoic

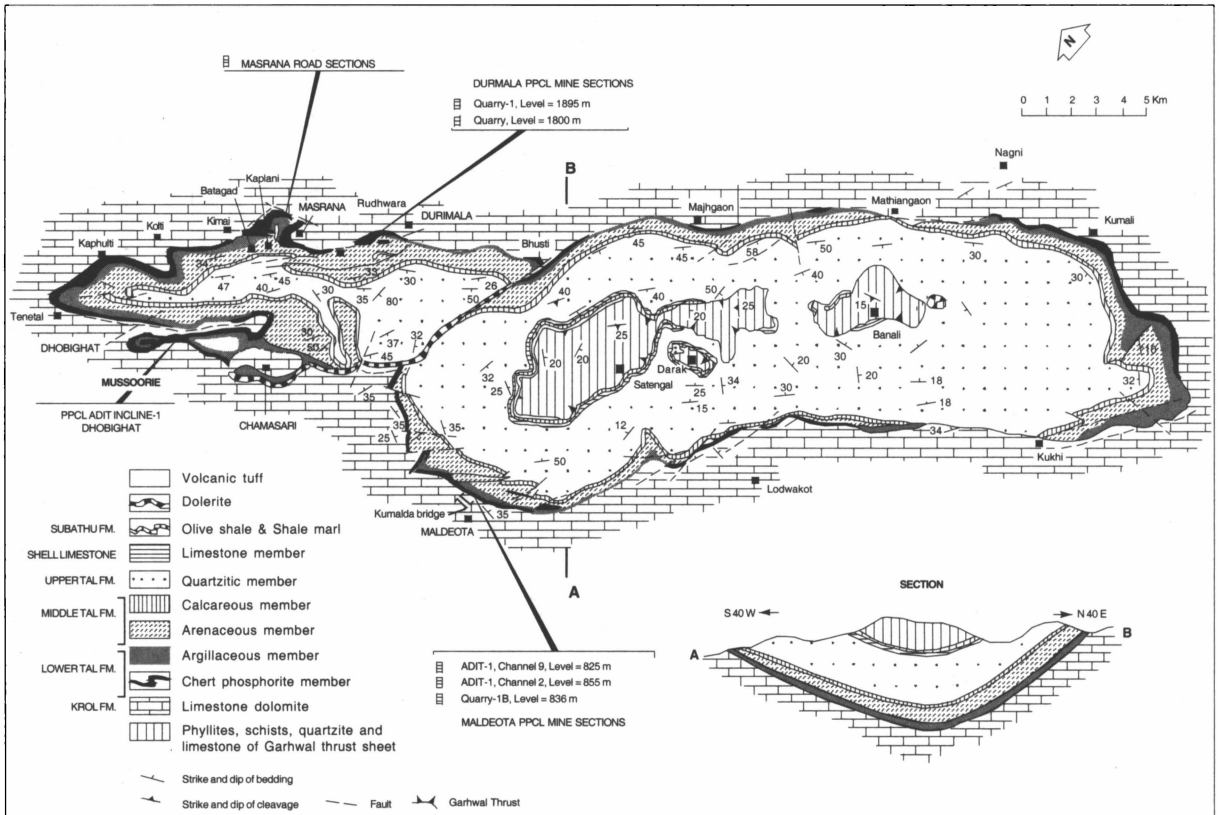


Fig.6.6. Geological map of part of the Mussoorie Syncline after Ravi Shanker (1975). Locations of important measured sections yielding Precambrian-Cambrian boundary shelly micro fauna are after Azmi (1983). A few other fossiliferous localities are also shown (source: Tandon et al. 1988).

(based on the assumption that the Blaini Boulder Bed was correlatable with Talchir Boulder Bed of Upper Carboniferous), but now it is fairly well established to be Vendian-Early Cambrian age.

Krol Belt: The following ediacaran fossils are recorded from the upper part of the Krol Formation in the Nainital syncline of Lesser Himalaya in Uttarakhand.

Beltaneliformis sp.cf. *B.brunsae*
Pterinidium sp.cf. *.P. simplex*
Ichnogenus Gordia sp.cf.*G. marina*

These taxa are comparable with the fossils present in the late pC Wernecke assemblage and ediacaran assemblage of other areas, particularly in Australia and Eurasia. The change from the smooth and unprocessed acritarchs in Blaini and Krol Formations to the first appearance of processed and spinate forms in Tal Formation (Chert Phosphorite Member) coincides with the appearance of the earliest skeletal fossils of Early Cambrian age.

The pre-trilobite fauna, bearing external shells or hard parts (excluding archaeocyathids) and defining the basal part of the Phanerozoic era are informally termed skeletal microfossils or small shelly fossils (ssfs). The ssf including *Coleoloides typicalis* Walcott, *Olivooides multisulcatus* (Plate 6.1), *Hyolithellus* sp. and *Turcutheca* sp. were recovered from a 150 m thick phosphate bearing section in the Colbert succession of Nainital syncline. The stratigraphic horizon of the ssf-yielding interval is represented by the Chert-Phosphorite Member of the Tal Formation in the Mussoorie (Figs. 6.6 and 6.7) and Garhwal synclines.

The Chert Phosphorite Member of the Lower Tal Formation in Korgai syncline offers a unique opportunity for studying Lower Cambrian biota. The microbiota include small acanthomorphic acritarchs, spheromorphs, cell clusters, isolated cells, rare filaments and sponge spicules. The assemblage is suggestive of a stratigraphic position of the Chert Phosphorite Member as close to the boundary or within the transition from Phanerozoic to Proterozoic.

A 3 m thick phosphorite band in the Tal Formation, Garhwal Himalaya is believed to mark the pC/C boundary following the discovery within it of the oldest small shelly fauna. This is well correlatable with that of zone 1 of Meischucunian Stage in China, the pre-Tommotian Manykaian Stage in Siberia and Yukon Territory of Canada. A strict upper limit to the age of this boundary is based on Rb-Sr date of 634±10 Ma for the carbonaceous black shales directly underlying the phosporite horizon. A good section of the entire Tal Formation can be met with on the Risikesh-Deoprayag Highway, on the right bank of the Ganga river between Kauriyala and Singtali villages.

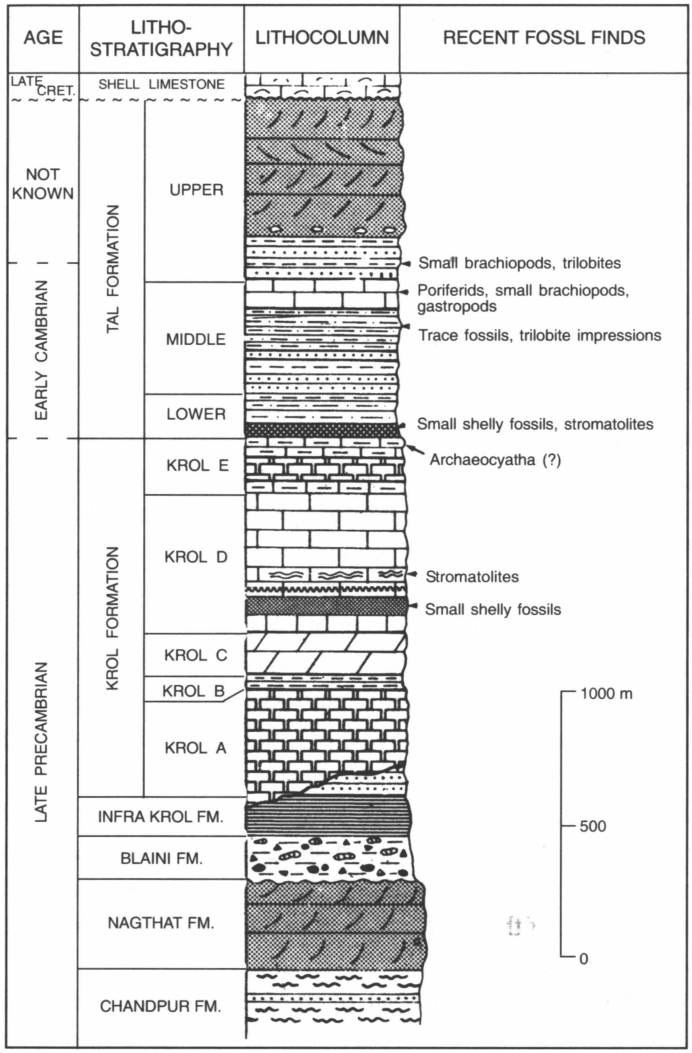


Fig.6.7. Fossiliferous horizons in Mussoorie section, Uttarakhand (source: Tandon et al. 1988, p.20).

Kashmir Sub-basin: In the late pC/C succession, NW Kashmir, two horizons of trace fossils are recorded in the Lolab Formation, one at 3,175 m and the other at 1,400 m below the Lower Cambrian body fossil zone bearing *Redlichia neotlingi*. The former horizon includes *Planolites* spp. and *Bergaueria* while the latter encloses *Taphrhelminthopsis,* besides *Planolites*. The trace fossils have been assigned to Eocambrian to low Lower Cambrian age. The sediments enclosing them are considered to have been laid down in intertidal sand and mud facies. *Taphrhelminthopsis* cf. *circularis* is the most common, occurring as a biolobate structure with well defined, and broad central furrow. *Helminthopsis* occurs as a groove in the Lidder valley.

Small shelly fossils (ssf) comprising of *Protohertzina Missarzhevsky* cf. *Taliella Azmi*, *Olivooides multisulcatus Quian*, *Gasparella porosa Missarzhevsky*, besides a new type of sponge spicule, were collected from a greyish black slate of the lower part of the Lolab Formation in the northern part of Kashmir basin. This assemblage occurs below the oldest trilobite (*Redlichia noetlingi*) and trace fossil *Rusophycus – Cruziana* zone, which clearly indicates that the boundary between the pC and the Cambrian lies within the lower part of Lolab Formation.

Spiti-Zanskar Sub-basin: The Zanskar sector of the Tethyan belt is the NW extension of the Spiti belt. Therefore for a clearer regional understanding it is necessary to adopt the terms already in vogue in Spiti and extend them to Zanskar region.

In the Zanskar sector, the following sequence of formations is observed in the basal Palaeozoic.

Upper Kunzum La Fm.	Dolomite/Shale	Late Middle Cambrian (Trilobites)
Lower Kunzum La Fm.	Silt/arenite/shale	Trilobite trace
Batal Formation	Carbonaceous shale, siltstone, arenite	

The Batal Formation is the basal unit of the Haimantha Group, lying over the Precambrian crystalline rocks variously designated as the flaggy quartzite and pyritous carbonaceous phyllite. It is assigned an Eocambrian age.

Rajasthan

The Nagaur-Ganganagar Evaporite basin in Rajasthan covers an area of about 50,000 km^2. It is an intercratonic basin with marine sediments of Late Precambrian to Early Cambrian age over the basement of Malani Igneous Suite and/or the Delhi metamorphites – between Kalu and Kaksar. The evaporite basin developed in the foreland slope of the Aravalli Range.

Over the Malani Igneous Suite (745±10 Ma) lie Jodhpur, Bilara, Hanseran Evaporite and Nagaur Formations of Terminal Proterozoic. Jodhpur Formation has yielded Microbially Induced Sedimentary Structure (MISS) that occurs in shallow water marine sand deposits near Sursagar in Jodhpur district. The Terminal Proterozoic is followed by Birmania Formationi. This is followed by Badhaura and Bap Formations.

Whereas in the Lesser Himalaya, the pC/C boundary is reasonably-well known, in the Aravalli-Vindhyan belt and the Greater Himalaya it is tentative.

CAMBRIAN

Though forming the first period of the Palaeozoic era, the strata belonging to this period are not necessarily separated by any profound unconformity from the underlying Precambrian strata in all the places where they occur, rendering it difficult to define sharply the boundary between the Precambrian and the Cambrian. This is compounded by the fact that the fossils of the Cambrian are far too varied to allow recognition of the first life among those of this period. Strata belonging to the Cambrian occur in the Tethys Himalaya as well as in the Lower Himalayan tectogens in the States of Jammu and Kashmir, Himachal Pradesh and Uttarakhand, though in the Lower Himalayan tectogens they are separated from Permian or Paleogene strata by a profound unconformity. In the Tethys Himalayan sectors, however, there is almost a continuous sequence of Palaeozoic strata followed by those of Mesozoic and Cenozoic with occasional minor unconformities.

The Nagaur Formation – the youngest of the rock formations of Jodhpur Supergroup in Rajasthan have yielded well-preserved trace fossils produced by trilobites, which give the trace fossil-bearing horizon a lower Cambrian age. However, this finding is yet to get unequivocal support from later workers.

Jammu and Kashmir

Cambrian strata are met with in the Kashmir Valley as well as the Zanskar sector of the Spiti-Zanskar belt. Of all the known Cambrian rocks of the Himalaya, the Kashmir Cambrian is by far the most accessible and complete, although the fossil horizons are considerably restricted compared to those of the younger Palaeozoic systems. They extend from Hundawar in the northwest of the Kashmir valley to Lidder valley. Good sections are seen in the Lidder valley, in the Basmai anticline in the Sind valley, in the Vihi district and in the Shams Abari syncline on the border of the Kashmir valley. 'Dogra Slates' in the Kashmir Valley pass through passage beds into strata bearing many indeterminable but definite organic remains and these in turn conformably pass into beds containing recognisable trilobites and brachiopods of Middle/Late Cambrian. Hence the passage beds with indeterminable organic remains (now some of them known to be identifiable trace fossils) probably include both Cambrian and Late Precambrian forms.

Early Cambrian: These consist of dark laminated slate with quartzose partings. Annelid markings in the form of convolute, straight casts, tube tracks, burrows are noticed. The Lolab Formation of Lower Cambrian age consists predominantly of laminated slates and quartzose partings or bands. Trace fossils

have been identified, far below the definite brachiopod and trilobite body fossils in the Cambrian sequence of Zanskar (Ladakh Himalaya). These are particularly noted in the Kurgiakh area of Zanskar.

Middle and Late Cambrian: In the foot of Shams Abari Hill the Early Cambrian passes into Middle and Late Cambrian exposed in a syncline. It consists of thin bedded, unlaminated but imperfectly cleaved clays of bright blue colour, grey and green micaceous sandy slates and brown ferruginous sand-stones. The argillaceous beds are copiously interbedded with limestones carrying many oolitic and pisolitic layers. Crowds of trilobites, obolaceous brachiopods with Middle and Upper Cambrian affinities are met with in some places.

In the Zanskar Tethyan belt, which is the NW extension of the Spiti belt, an association of micaceous quartzite, flaggy quartzite and pyritous carbonaceous phyllite, gritstone and sporadic lenticular limestone occur in various alternations. These constitute the basal unit of the Haimanta Group and are referred to as the Batal Formation. These rocks are exposed from the Shiinkun La to Tsarp Lingti Chu valley through Padam, Doda valley to Ringdom Gompa and again in Suru valley. Some have, however, used the term Phe Formation, which was also applied to the Permian Volcanics in Zanskar. The Batal Formation is unfossiliferous and can be assigned Terminal Proterozoic to Eocambrian age as it underlies the Kunzum La Formation, which is the principal Cambrian unit.

In the Zanskar area, the Kunzum La Formation succeeds the Batal with a gradational contact. This formation is also referred to as the Karsha and Kurgiakh Formations. It extends from Lingti valley in the SE to Padam valley in Zanskar in the NW. The Kunzum La is divided into lower and upper formations. The lower Kunzum La Formation is characterised by a sequence of olive green shale, siltstone, argillite, slate, phyllite, quartzite and greywacke in regular alternations. The upper Kunzum La Formation contains massive to bedded thick brown weathered dolomite, cross-bedded calcarenite and quartzite with interbeds of shale and siltstone.

The Cambrian sequence of Zanskar was considered to represent an intermediate depth level between the outer and inner shelves, the former being represented by the Spiti sequence and the latter by the Kashmir sequence, though such an inference is disputed now.

The following trilobites have been recorded from Kurgiakh area of Kunzum La Formation of Zanskar Basin:

Ptychoparia, Lyriapsis, Anomocarella, Anomocaraspis, Hundwarella, Elrathia, Eymekops, Damsella, Lisania

Figure 6.8 shows the distribution of brachiopods and trace fossils in the Cambrian of Kashmir from various sections in the Pohru Valley in the Lolab, Sagipura, Nutunus and Trahgam Formations. Three bio-zones of the Lower, Middle and Upper Cambrian are also indicated and the bulk of the fauna is considered to be of a cosmopolitan nature. Spores and tracheids are also reported from the Cambrian of Kashmir.

Himachal Pradesh

Cambrian strata occur both in the Tethys Himalayan zone and Lesser Himalayan zone in Himachal Pradesh. The Kunzum La is the principal Cambrian Formation of Lahaul-Spiti-Kinnaur sub-basin (including Zanskar) in the Tethys

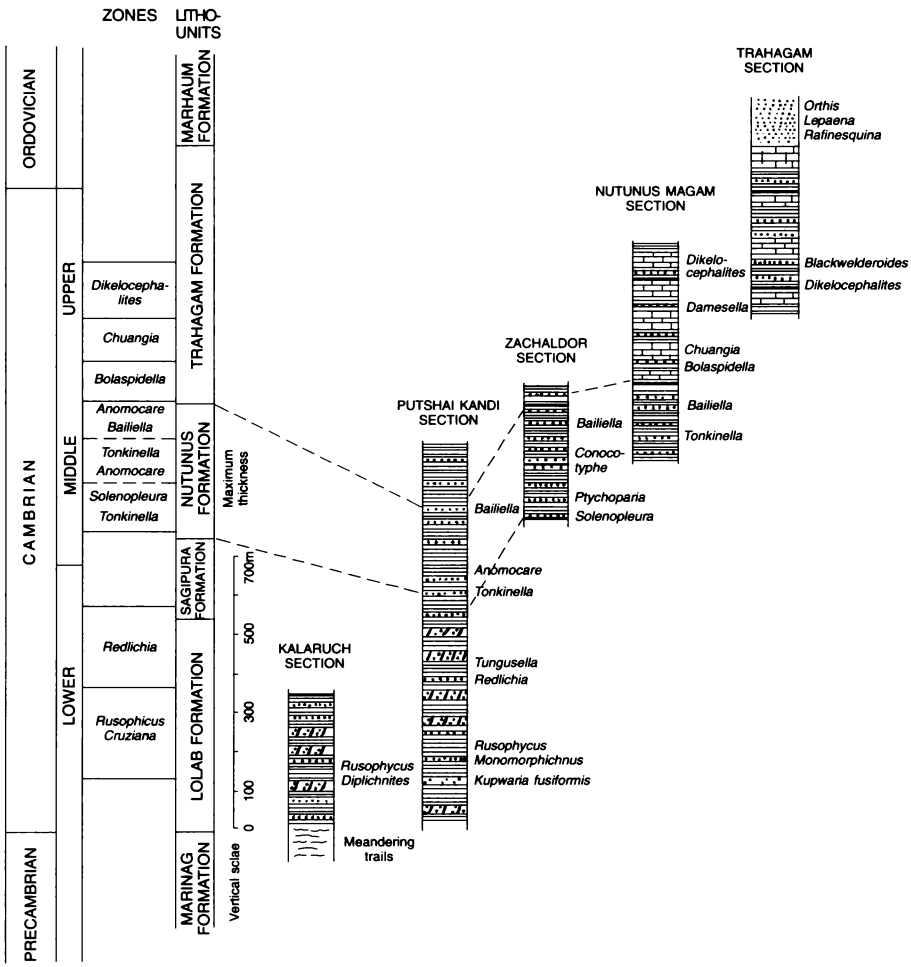


Fig.6.8. Biostratigraphy of the Cambrian of Kashmir from various sections in the Pohru Valley (after Shah, 1982; © 1982; reprinted with permission from Elsevier).

Himalaya. It comprises a greenish grey siltstone, shale, slate, quartzite and dolomite and ranges in age from Early Cambrian to Middle Cambrian. The pC/C boundary lies in the upper part of the underlying Batal Formation; the Kunzum La Formation in its basal part encloses trace fossils of *Treptichnus pedun, Plagiogmus* and many others. Primitive brachiopods are also met with a little higher up in the sequence besides trilobites *Ptychoparia, Oryctocephalus, Lingulella haimantensis, Redlichia noelingi* etc., of Middle Cambrian age. Conodont fauna *Oneotodus* spp., *Agittodontus* sp., and *Furnishiana* have been reported from the upper Kunzum La Formation.

From the Kunzum La Formation (Haimantha Group of the Pin section in Spiti Valley) the following trace fossils belonging to Lower Cambrian are reported:

> *Planolites, Skolithos, Psammichnites, Neonereites, Rusophycus, Didymaulichnus, Monomorphichnus, Dimorphichnus, Diplichnites, Plagiogmus* and *Cruziana.*

The Agnostid fauna (trilobites) from the Middle Cambrian of Parahio valley in Spiti includes *Peronopsis amplaxis* and *Pagetia greisbachi.* This assemblage is correlated with *Solenopleura-Tonkinella* zone (see Fig. 6.8) of Kashmir. In the dolomite bands of the Parahio Series of Hayden in Spiti, conodonts and Middle Cambrian trilobites have been reported.

Tal Basins

In the Lesser Himalayan tectogen the Tal Group represents the late Early Cambrian in the Tal basins of the Inner Krol basin. The Tal formations occur in the cores of four separate synclines of the Inner Krol belt of which the Nigaldhar and Korgai are situated in the Himachal Himalaya (Himachal Pradesh) and Mussoorie and Nainital synclines in Uttarakhand. Tal formation is not reported from the Outer Krol Belt.

The Tal Group is divided into Shaliyan, Sankholi and Koti Dhaman Formations. The comparison of the Tal sequence of Mussoorie (in Uttarakhand) with that of Nigaldhar of Himachal Pradesh has shown that the Chert-Phosphorite Member of the former is part of the basal Shaliyan Formation of the latter. A comparison of the micro-shelly forms found in the Tal Group in Himachal Pradesh with allied forms in other parts of the world conclusively places them on the evolutionary column along with other Lower micro-shelly fauna. Shaliyan Formation of the Tal Group is Lower Tommotian, i.e. earliest Cambrian in age.

The upper part of the Tal Formation exposed in the western part of the Nigaldhar syncline on the southern slopes of the ridge about 800 m NE of

Ganog in Sirmur district of Himachal Pradesh contains *Redlichia noetlingi, Redlichia* sp. (trilobites) and *Obolella* sp. and *Lingulella* sp. (brachiopods). This find assigns an early Cambrian age to these rocks. The trace fossils reported from here include *Rusophycus, Monomorphichnus, Diplichnites, Gordia* and *Astropolichnus*, all referable to Early Cambrian.

The Middle Cambrian transition is represented by continuous sedimentation in Kashmir, where the *Bolaspidella* zone bearing *Diplagnostus* marks the uppermost horizon of Middle Cambrian, whereas *Damesella* zone indicates the beginning of Late Cambrian. A barren zone marks the transition in Spiti.

The Tal Group represents variable phases of sedimentation passing into a mixed flat and mud flat lagoon and embayment, then into a mixed flat and mud flat of intertidal zone, terminating with a deposit characteristic of shoal complex of a tidal sea.

Uttarakhand

Excellent sections of the Tal Formation overlying the Krol Formation are met with in parts of the Mussoorie Syncline in Uttarakhand of the Lesser Himalayan tectogen (Fig. 6.6). This formation starting from the base consists of the following units: Chert Phosphorite Member, argillaceous, arenaceous, calcareous, and quartzitic and limestone. Stromatolites and small shelly fossils are met with even in the Krol Formation (Fig.6.7) in the Chert Phosphorite Member, exposed in the PPCL Mine at Maldeota in Dehra Dun district. Small shelly fossils, precisely correlatable with fossil zones from other well-established Early Cambrian sequences in the world, are also met with. The presence of phosphorite at the base of the Tal Formation establishes the presence of global Cambrian Phosphogenic Province in the Indian subcontinent as well.

First record of siliceous hexactenellid and desmosponge (?) spicules from Lower Tommotian chert and phosphorite of the Lower Tal Formation is also reported from the Mussoorie and Garhwal synclines.

In the Tethyan belt of Kumaun, near Garbyang in northern Kumaun, the Precambrian Budhi Schist is unconformably overlain by about 2 km thick succession of calcareous shales known as Garbyang Formation. In the western extension, the Martoli Formation intervenes between the Budhi Schist and the Garbyang Formation. The Garbyang Formation has been assigned Cambrian age on the basis of flat gastropods recovered in the Niti Pass area of the Chamoli district. The upper part of the succession has yielded ribbed brachiopods and flat gastropods of Middle Ordovician age.

Reconnaissance Re-Os age of black shales from the Lower Tal section of

the Lesser Himalayan sedimentaries is 552±22 Ma, which is consistent with their palaeontological correlation with pC/C boundary.

Correlation

The biostratigraphy of the Himalayan Cambrian is succinctly classified in Fig.6.9. Several conclusions are drawn from the distribution of the biostratigraphic record.

(i) The earliest trilobites known from the Himalaya are of late Early Cambrian (Tsanglangpuian) age.
(ii) The top of the Spiti section correlating with the base of the Kashmir section is partly the result of biostratigraphic differences between the areas.
(iii) Faunal differences occurring between contemporary Kashmir and Spiti fauna are likely the result of biofacies differences.
(iv) None of the taxa in either basin (Kashmir and Spiti) is exotic to the equatorial peri-Gondwana realm.

The Himalayan Cambrian trilobite fauna is consistent with the passive margin model for the northern margin of India and with current concepts of regional land mass distributions. The faunal similarity of Himalayan sequences with those of South China supports the argument that the South China block was the complementary passive margin to the Himalaya during the earliest Phanerozoic.

ORDOVICIAN AND SILURIAN

Rocks belonging to the Ordovician and Silurian occur together. Either due to paucity of fossils or due to considerable thickness of unfossiliferous strata separating Ordovician and Silurian, it has not been possible to place the boundary between them with any degree of reliability. Strata belonging to both the systems occur in the Himalaya in Kashmir (Jammu and Kashmir), Spiti-Kinnaur (Himachal Pradesh) and Kumaun-Garhwal (Uttarakhand). Fossiliferous Ordovician rocks underlie the uppermost part of Mount Everest.

Jammu and Kashmir

The Ordovician can be considered to be partly or wholly represented by *Lihinwan* and *Refinesquina* horizon in Anantnag district, *Orthis-Leptaena* in Barmulla district, part of Baflial volcanics and associated slate in Poonch district, slates and phyllites in Sind valley and upper part of Ramsu Formation

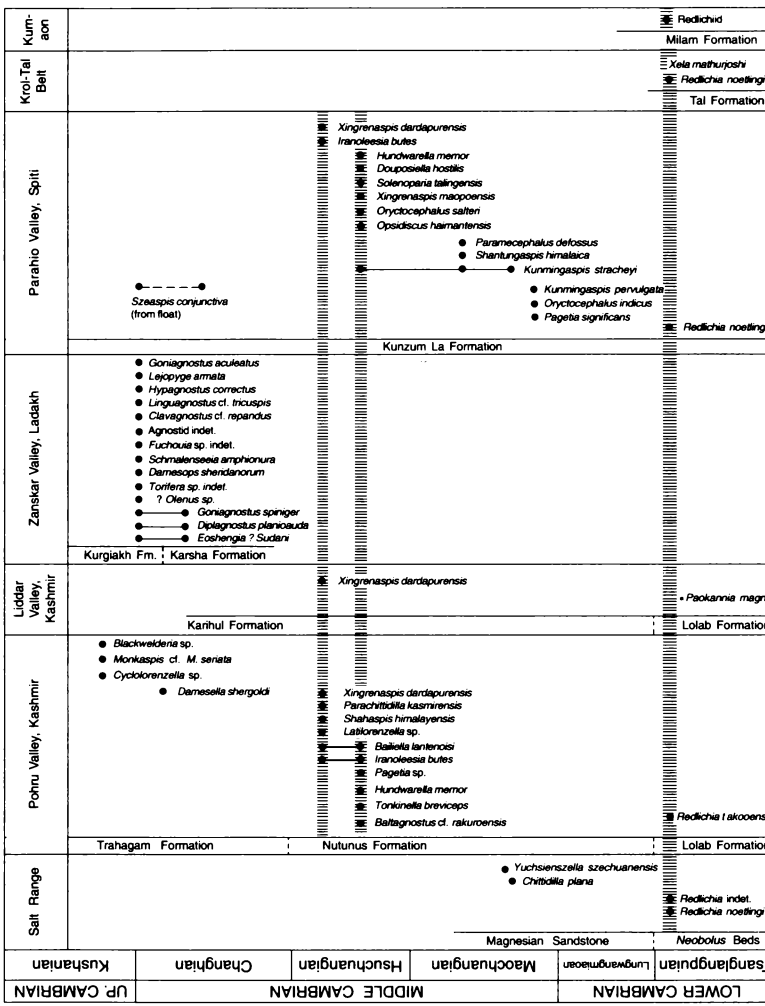


Fig.6.9. Biostratigraphic scheme for the Himalayan Cambrian. The Chinese stadial system is applied to the faunas of the region. Outcrop belts are ordered from west to east. Bullet points and vertical lines above taxon names indicate stratigraphic ranges; horizontal bars indicate correlations among outcrop regions. The names of local lithostratigraphic formations are shown to the left of taxonomic ranges. Dashed boundaries between formations indicate that the biostratigraphic position of the boundary is uncertain. (after Hughes, 1997; reprinted with permission from Current Science).

in Doda district. In Shans Abari syncline, about 19 km southwest of Handwara, a large exposure of variegated slates with numerous distorted fossils is found overlying the blue clays of Cambrian age. These rocks have been referred to Ordovician.

Orthis, Leptelloidea, Leptaena, Strophomena, Refinesquina, Resserella, Sowerbyella, Raymondella, Antiella and crinoid stems are reported from the Shans Abari syncline area.

In the Lidder valley of Anantanag district, there is a fossiliferous shale horizon called Gauran Beds of Late Ordovician age, which yielded bryozoans, brachiopods and cystids. The entire succession from late Cambrian to Silurian is designated as Hapatnar Group, though the latest Cambrian is absent. There is an unconformity between Cambrian and Ordovician-Silurian. The Shans Abari syncline is also considered to contain Silurian strata hosting crushed and obliterated Silurian fossils.

Near Anantanag, about 30 m thick blue grey, rusty weathering sandy shales with definite upper Silurian fossils succeed older slates of Cambro-Silurian age. In lower reaches of Sind valley, Ordovician greywackes and slates are succeeded by Silurian slates, which in turn are followed by typical Muth Quartzites. The slates are, however, devoid of fossils. In Kashmir, the Ordovician and Silurian strata are also named as belonging to Rishkobal A (Hallamulla) and Rishkobal B (Gigaldhar) respectively.

The syncline containing Palaeozoic succession in Warwan valley of Doda district contains a thin band of fossiliferous Silurian below the Muth Quartzite and above the Dogra Slates. Rocks bearing definite Silurian fauna have been located in Halmatpura area. The Ordovician-Silurian fossils in this area are rich in brachiopods. Bryozoan and trilobite impressions are also met with occasionally.

The Thango Formation overlying the Kunzum La Formation in the Zanskar range, consisting of a sequence of conglomerates, quartzites and slates and characterised by typical purple colouration as seen in Kuneak valley, has been assigned a Silurian age by some.

Himachal Pradesh

Thango Formation: Referred to the Ordovician, this is separated by an unconformity from the underlying Kunzam La Formation in Pin and Chorgal valleys. This is well exposed in the Parahio river section in Spiti area. The formation can be well recognised because of its characteristic crimson/maroon colour and rugged topography. The upper contact of the Thango Formation with the Takche Formation is gradational (Fig.6.10). The Thango Formation is essentially an arenaceous sequence, which in most sections, begins with a

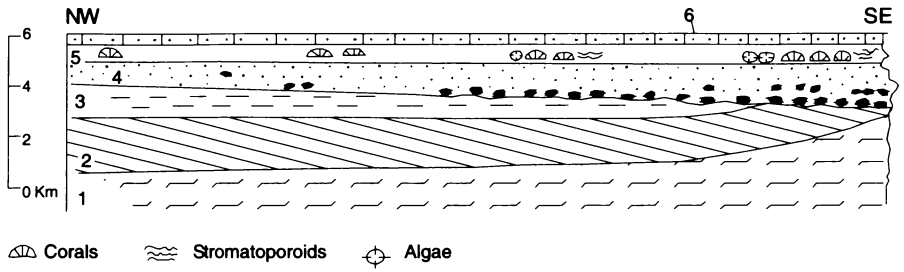


Fig.6.10. Relative stratigraphic position of the Takche/Manchap Formation. (**1**) Batal Formation (Eocambrian), carbonaceous phyllite, slate, quartzite. (**2-3**) Kunzam La Formation, (**2**) Debsa Khad Member (Eocambrian to lowermost Cambrian), grey shale-slate sandstone, locally carbonaceous. (**3**) Parahio Member (Lower to ?Middle Cambrian), grey-green shale, slate, sandstone, dolomite. (**4**) Thango Formation (Orodovician to earliest Silurian), red siltstone, fine-grained sandstone, conglomerate at the base and shale intercalations in the upper part. (**5**) Takche/Manchap Formation with reefal buildups. (**6**) Muth Formation (Early Devonian to Early Upper Devonian), white mottled sandstone (after Bhargava and Bassi, 1999).

conglomerate bed. Purple quartzite, siltstone and shale follow this. Shaly partings usually contain well- preserved trace fossils.

Numerous small sills of gabbro-norite affinity are observed within this formation in the Tidong and Gyamthing valleys.

The sedimentation of the Thango Formation commenced with fluvial material reworked on beach, and passed through essentially a tidal zone with storm episodes where wave action was prominent. Towards the terminal phase, by and large, there was decrease in energy level, possibly due to relative deepening. The entire sedimentation took place under oxidizing conditions.

The following fossils are reported from Kinnaur:

Body fossils: *Raphistoma, Pentamerus, Trochonems, Propora himalaica, P. (Lyella) americana.*

Trace fossils: *Phycodes cincinatum, Arenicolites, Planolites, Skolithos, Teichichnus, Rusophycus, Rouaultia, Monomorphichnus.*

This formation together with the overlying Takche Formation is included in Sanugba Group. The lower age limit of Thango Formation is Lower Ordovician because of the presence of trace fossil *Phycodes circinatum,* index fossil of Lower Ordovician. It may range in age up to early to middle Ordovician.

The equivalent of Thango Formation in Kashmir is Member A of Rishkobal Formation. In Kumaun it is equivalent to Shiala Formation.

Takche Formation: This formation in Spiti valley was designated as Manchap in Kinnaur in the past and is roughly assignable to Late Ordovician to Middle Silurian. Being rich in carbonate, it is easily recognisable from a

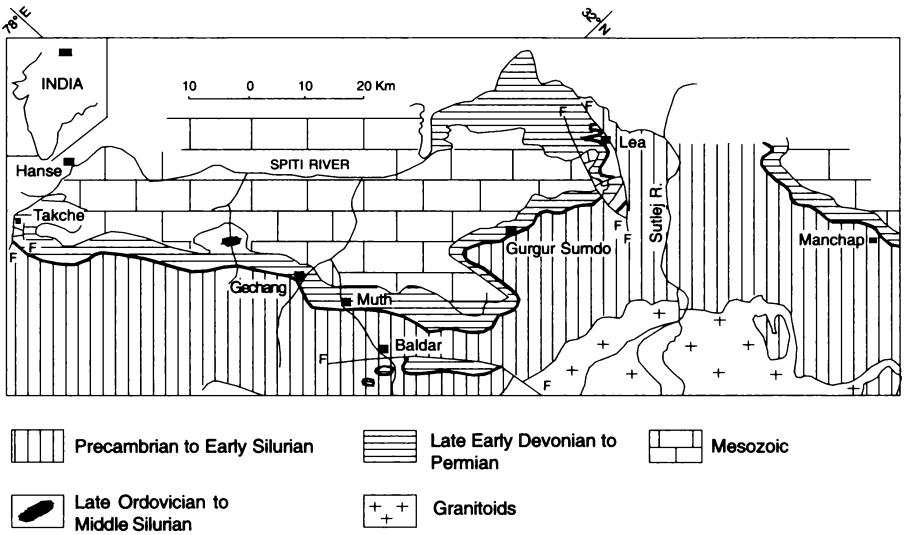


Fig.6.11. Geological sketch map of Spiti-Kinnaur area (modified after Bhargava and Bassi, 1999, p.36).

distance by its earthy brown appearance, sandwiched between the purple Thango Formation below and white coloured Muth Formation above. The stratigraphic position of the Takche/Manchap Formation is illustrated in Fig.6.10 and a geological sketch map of the Spiti-Kinnaur area indicating the location of the formation in the area in Fig.6.11.

Small transgressive sills of dolerite intrude Takche Formation in the Tariya and Manchap areas. The contact of Takche and the overlying Muth Formation is sharp and disconformable. There is considerable variation in the lithology of the Takche Formation in the different sections. It varies from sandstone to shale to limestone to dolomite with a lot of facies changes in them giving rise to wacke, mudstone, packstone, floatstone etc. Besides these, there have been considerable reefal build-ups by colonies of corals, some of which are 30 cm wide. The reef builders are essentially corals, stromatoporoids and solenoporoides.

The following are among the fossils from the Spiti area:

Corals: *Streptelasmids, Favosites, Halysites, Heliolites, Coenites.*
Brachiopods: *Orthis, Atrypa, Chonets* (Plate 6.3) *Pentamerus, Leptunea.*
Bryozoans: *Hallopora, Fenestella, Dianulites, yak, Atactaporellis sp.*
Conodonts: *Amorphognathus, Panderodus.*
Algae: *Apidium indicum, Girvanella sp., Vermiporella sp., Cyclocrinites.*
Trace fossils: *Arenicolites, Arthrophycus, Chondrites, Planolites.*
Others are orthocerathids, gastropods, crinoids, and echinoderm spines.
Most of the fossils have been crystallised.

There are several taxa among the fossils, which are characteristic of both Ordovician and Silurian. Based on algae and corals, and now confirmed by conodonts, the Takche Formation ranges from late Ordovician to middle Silurian with reefal representatives. *Halysites* is considered to range up to but not later than Silurian. It occurs up to the top of the Leo and Manchap reefs, which are overlain by *Psilophyton* (plant) bearing sandstones. Therefore the upper boundary of the reefs must still be within Silurian. Reed fixed the Ordovician-Silurian boundary in the Spiti valley with the help of *Propora himalaica* and *P. (Lyella) americana*. The extension of Takche Formation in Kumaun (Uttarakhand) has been described as the Yong Limestone and also as Variegated Formation, which show massive stromatoporoid colonies.

Uttarakhand

There is a succession of variegated shales with sandy limestones and crinoidal breccias above the Garbyang Formation in northeastern Kumaon in Garhwal Himalaya. The upper part of the Garbyang Formation with ribbed brachiopods and flat gastropods is assigned a Middle Ordovician age. The Shiala Formation has a rich assemblage of Ordovician fossils that includes *Calymene, Orthis, Refinesquina, Strophomena*, crinoid stems and oscicles. The trace fossil assemblage in the Shiala Formation includes *Chondrites, Loranzina, Planolites* and *Skolithos*.

Figure 6.12 is the geological map of the Sumna-Rimkhim area of the Tethyan zone of the higher Garhwal Himalaya indicating the distribution of Ordovician and Silurian horizons (4, 5 and 6) among the older and younger formations of the area.

The Shiala Formation contains the conodont, *Amorphognathus tvaerensis* Bergstrom, which indicates a Middle Ordovician age. Acritarchs – *Sphaeromorphs, Acanthomorphs* and *Herkomorpha* are found in the Shiala and Yong Limestone Formations. The presence of age marker forms of acritarch reveals that the Ordovician-Silurian boundary lies within the Shiala Formation.

The following are among the fossils in these formations:

Garbyang Formation:	Trace fossils – *Cruziana, Gyrochorte, Phycodes, Planolites, Rusophycus, Isopodichnus.*
Shiala Formation:	*Calymene* (trilobite); *Bellerophon* (gastropod); *Orthis, Orthothetes, Rafinesquina, Sowerbyella* (brachiopod); acritarchs and trace fossils.
Variegated Formation:	*Orthis (Dalmenella) bouchordi; Favosites*

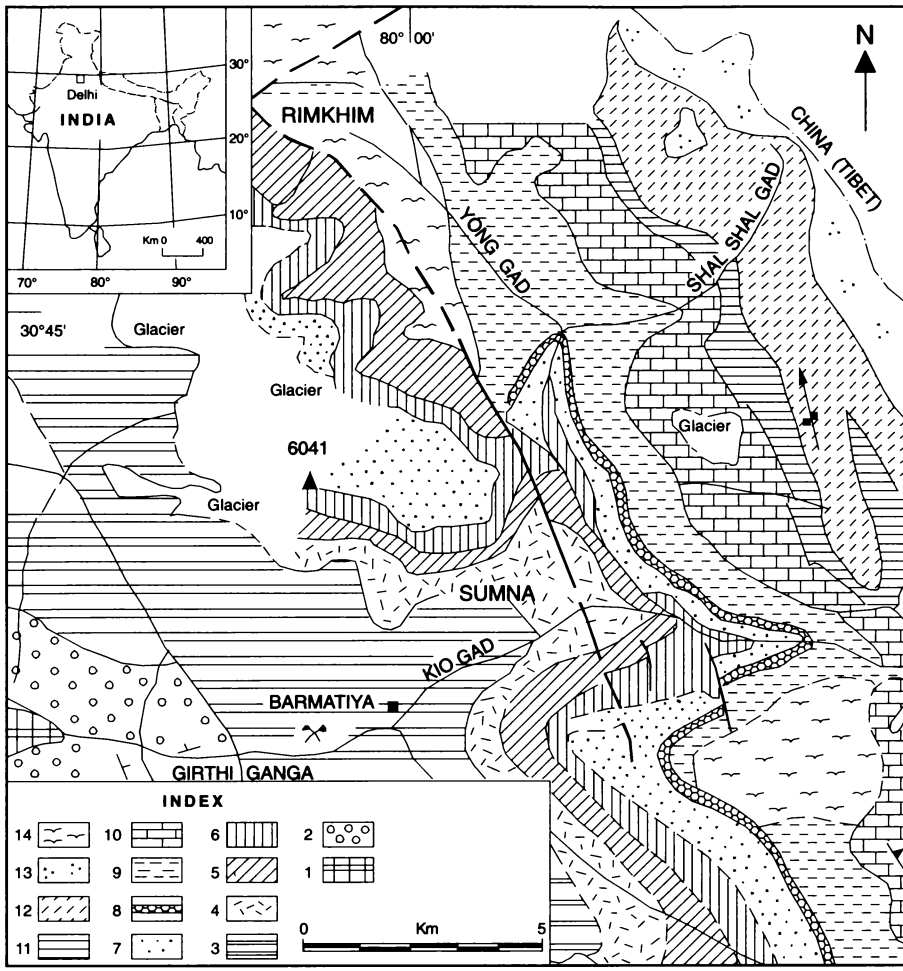


Fig.6.12. Geological map of the Sumna-Rimkhim area of the Tethyan Zone of the higher Garhwal Himalaya, India (Sinha, 1989). **1** - Martoli Group; **2** - Ralam Formation; **3** - Garbyang Formation; **4** - Shiala Formation; **5** - Yong Limestone Formation; **6** - Variegated Formation; **7** - Muth Quartzite Formation; **8** - Kuling Shale-Fenestella Shale; **9** - Kalapani Limestone Member/Kuti Formation; **10** - Kioto Formation; **11** - Lapthal Formation; **12** - Spiti Shale; **13** - Giumal Sandstone; **14** - Alluvium (after Sinha et al. 1998; © 1998 reprinted with permission from Elsevier).

DEVONIAN

Stoliczka first used the term Muth Series from Muth village in Spiti to describe a sequence of lithounits between what he termed Bhabeh Series and Kuling Series. He assigned an Upper Silurian age to these lithounits. However, later Hayden found the lower and middle parts of the sequence to be Silurian, but considered the upper part, the white Muth Quartzite, not younger than Devonian. The term Muth Formation is now being adapted to

this white quartzite, which can be recognised from a great distance and can be easily picked up on aerial photograph and is an important marker unit in the Palaeozoic sequence in the Tethys Himalaya extending from Kashmir to Kumaun.

Jammu and Kashmir

In the Kashmir region, the Muth Quartzite is exposed on both flanks of the Lidder anticline as thin beds. In the Warwan area massive unfossiliferous quartzite of Devonian age reappears in a synclinal fold with thin-bedded siliceous shale at the base, passing downward into upper Silurian fossiliferous beds. The Muth Quartzite is also present in the lower reaches of the Sind valley and also in Shams Abari syncline of Handwara, in the syncline in Zanskar-Rupshu area and north of Pongong Lake and the Shylok valley. The inference of the age of the Muth Quartzite is based purely on its stratigraphic position.

In the Jammu region, the Muth Quartzite of Naubagh valley, when traced towards southeast, extends across the Saribal Range into the Warwan valley of Jammu Himalaya. The quartzite band, which is underlain by the Silurian and is overlain by the Syringothyris Limestone or Panjal Trap, is repeated four times due to folding into several anticlines and synclines. It is a very conspicuous marker horizon, which is very helpful in strike mapping and in working out the fold patterns. In Jammu region in the southwestern flank of Pir Panjal Range in Markoi-Baramgala, the Dogra Slate rests over Salkhala, which are unconformably overlain by a basal conglomerate of the Tanawal. These are considered to be equivalent to the Talchir Boulder Bed and hence can be only Late Carboniferous-Early Permian.

Rare plant remains from Kotsu Hill and Diwth Spur in Kashmir, are the only record of plant life in the Devonian- *Toeniocrada* sp. and *Protolepidodendron* sp. There are no definite pre-Devonian records of land plants in India.

Himachal Pradesh

The Muth Formation rests on Takche Formation along a sharp contact, indicating a possible break in sedimentation in the Spiti valley. Its upper contact with Lipak Formation is intercalated. Near Guimdo (Spiti valley) it rests over the Precambrian Vaikrita Group. In Kinnaur, along an unconformity, it is succeeded by the Kuling Formation. Along the upper contact, the Lipak, Gechang and Gungri Formations invariably overlap the Kuling, and the contact is sharp. At Jongchen it shows an undulatory erosional top below the Gungri Formation.

The entire sequence of Muth Formation is composed of fine to medium grained white sandstone. It has more or less uniform thickness in the main Spiti valley. At places sporadic conglomerate lenses occur. In the Kinnaur basin it is uniformly developed with thickness varying between 80 and 120 m.

The presence of trace fossils indicates a littoral zone of deposition. The prevalence of herringbone cross bedding is suggestive of tidal currents, also substantiated by subaerial and subaqueous mud cracks and interference ripples. Beach conditions varying from beach foreshore to wave zone and dune ridges are very much indicated. Aeolian deposition recognised by high angle cross bedding mixed with water-worn sand grains gives rise to a bimodal sand of Muth. Total absence of body fossils and general absence of trace fossils together with certain types of bedding features are indicative of transgressive upper shore facies to beach environment.

Conodonts (Plate 6.2 – 13, 14 and 15; Plate 6.3 – 4, 5 and 6) have been reported in Kashmir, Kishtwar and Ladakh. Muth foassils are: *Paleophycus, Planolites, Skolithos,* and arthropod trackways, *Diplichnites goudi, Diplodicnus biformis, Palmichnium antarcticum, Selenichnites* sp., *Taemidium baretti,* orthoceratid, *orthis* aff. *rustica.*

In the Kinnaur basin, *Orthis rustica* is found in a horizon 70 m above *Psilophyton* bearing beds from the Muth Formation pointing to a Devonian age. The Muth Formation has a conformable contact with the overlying Lipak Formation, which ranges in age from middle Devonian (Givetian) to early Carboniferous. In view of this conformable contact, the upper age limit of the Muth Formation has to be within Devonian, possibly Early Devonian to early Middle Devonian. Thus Late Silurian is absent in Spiti-Kinnaur defining a hiatus between Takche and Muth.

Uttarakhand

In northern Kumaon, the Muth Formation represents both the Upper Silurian and Devonian. It consists of quartzite with dolomite layer, overlain by massive white quartzites, typical of the Muth in the Spiti region. A crinoidal limestone in the Lipu-Lek area represents the Devonian. In the Malla Johar area of Kumaon basin, *Atrypa reticularis* (Plate 6.2- 5) and *Schellwienella willigmi* are reported, of Devonian age, besides a few fragmentary plant fossils.

The boundary between Devonian and Carboniferous in Spiti valley is located within the Lipak sequence where Devonian and Carboniferous corals have been found. In this section, it remains fluid because of lack of the sequence containing undoubted Late Devonian and Early Carboniferous biota.

In Byans, Devonian fossils have been found in some dark limestones near Tera Gadh Camp. These include: *Atrypa reticularis, Pentamerus* cf. *sublinguifer, Camerophonia* cf. *pillipsi, Rhynchonella (Wilsonia)* cf. *omega, Orthis* aff. *bistriata* and also the cephalopod *Orthoceras* and the coral *Favosites.*

CARBONIFEROUS

In some parts of the world, the Carboniferous is fully developed with both terrestrial and marine sequences, some of them containing the world's largest reserves of coal. In the Indian subcontinent, however, the marine is mostly in the Himalayan belt with a hiatus in the Upper Carboniferous. The uppermost part of Carboniferous is, however, present in Peninsular India, forming the base of the Gondwana Supergroup. Besides, glaciation was initiated during this period only for a short while during the late Carboniferous.

Strata of Carboniferous age are met with in the Kashmir sub-basin of Jammu and Kashmir, Spiti-Zanskar-Kinnaur sub-basin in Himachal Pradesh, Kumaun sub-basin in Uttarakhand, besides in Nepal, Sikkim and Bhutan. They are reported from Karakoram as well. All these are essentially marine strata. An interesting feature is the intercalation of plant beds in a few of them, particularly in the Kashmir sub-basin, which show that some of the species are related to those of the Gondwana of Peninsular India and some to those of the northern region of Angaraland. Towards the end of Carboniferous and mainly in the Lower Permian, marine intercalations are met with in terrestrial strata of Gondwana in parts of Peninsular India. These are of significance in not only arriving at the palaeogeography of the Central Indian region, but also of great aid in precisely arriving at the age of the associated terrestrial strata, namely in the Lower Gondwana.

Jammu and Kashmir

In Kashmir sub-basin, the Carboniferous is represented by Tannaki Conglomerate, Syringothyris Limestone and Fenestella Shale.

Tannaki Conglomerate: In the Bhadarwah-Bhallesh area, the Sunbain quartzite conformably passes upward to a persistent boulder bed/conglomerate horizon, referred to as Langera Conglomerate, which occurs at the base of the fossiliferous Carboniferous-Trias sequence of Bhadarwah-Chamba synclinal basin. Tanawal, Tanakki and Langera Conglomerates, though considered upper Carboniferous, could possibly be Precambrian. The base of the Carboniferous-Permian represents a major unconformity. The large conglomerate outcrops

all around the Carboniferous-Trias marine basin. The thickness of the conglomerate varies from about 40 to about 300 m.

Syringothyris Limestone: This unit consisting of a series of limestone beds, mostly flaggy, is well exposed in the Lidder anticline of Aishmuqam of Kashmir region. Named after the index fossil *Syringothyris cuspidata* (Plate 6.2- 18), which is found in abundance, this unit is correlated with Lipak Formation of Early Carboniferous of Spiti. *Chonets* and *Productus* are also found in large numbers. In Jammu region, these rocks are exposed near Banihal, near Pir Panjal Range, in Warwan Valley and in Bhadarwah-Bhallesh sub-basin.

From the base of the Syringothyris Limestone, exposed in the Lidder valley near Aishmuqam, in the isolated hill near Kotsu, the following conodonts have been reported: *Clydagnathus gilwerensis, Polygnathus communis communis, Bipathodus stabilis, Neoprioniodus confluens, Ozarkodina macer* and *Hindeodella subtilis.* The last four are considered to belong to Lower Carboniferous (Early Tournaisian).

In the Chavil-Nawagan section, north of Banihal in Kashmir, in Gund Formation the following plant fossils of Lower Carboniferous age are found: *Archaeocalamites radiatus*, *Archaeosiggilaria* sp., *Lepidosiggilaria quadrata* and *Lepidodendropsis siggillariode*, the last being a primitive land plant. The plant bearing horizons are marked ///// thus in Table 6.2 within the Upper Palaeozoic sequence, and the lithology of the different members belonging to the various formations is also given. Syringothyris Limestone and Fenestella Shale of Kashmir and Po Formation of Spiti contain well-preserved plant fossils of Lower Carboniferous. However, no Upper Carboniferous flora is known from India so far.

Fenestella Shale: In the Lidder valley, Banihal-Budil area, Desa-Singpore-Saribal Range and the Warwan valley, the Syringothyris Limestone is overlain conformably by a horizon of fossiliferous quartzite and shales with well preserved fossils of *Fenestella, Productus, Spirifer, Pecten* etc. The prominent peaks of Skami Range of Karakoram watershed are composed of a thick sequence of white and grey crystalline limestone with interbedded black shales, which yielded *Fenestella* in Punmah area.

Agglomeratic Slate: With a view to avoid naming of a formation after a fossil (like Syringothyris Limestone and Fenestella Shale) and after a single lithological unit (like Agglomeratic Slate), when it may be constituted of different lithological units, the name Lidder Group has been suggested (Srikantia and Bhargava, 1983) to the sequence of formations, earlier referred to by

Middlemiss as "Syringothyris Limestone," "Passage Beds," "Fenestella Shales," and "Agglomeratic Slate." This is now reclassified as Aishmuqam Formation, Ganeshpur Formation and Pindobal Formation in the ascending order. It derives its name from the Lidder river, which flows through an excellent section of this group (Table 6.1).

Aishmuqam Formation (Syringothyris Limestone): It consists of quartz arenite, calcarenite and siltstone. This contains *Syringothyris, Modiola, Fenestella* - A, B, C.

Ganeshpur Formation: It consists of quartz arenite, carbonaceous siltstone and shale. A, B, C, Diorite Sill, D.

Pindobal Formation: It is a diamictite unit associated with quartz arenite, siltstone and shale. This formation is devoid of volcanic element and is essentially a sedimentary unit of shallow marine environment (A, B, C.*Fenestella*). The upper part of the Pindobal Formation encloses *Eurydesma* of Early Permian age.

In the Zanskar sub-basin the Carboniferous strata appears in the southeast part of Zanskar and continues up to a little SW of Phise La, where they get overlapped by the Permian Phe Volcanics. The strata are represented by Lipak, Po and Ganmachidam Formations. Further SE they continue into Spiti-Kinnaur segment of the larger Spiti-Zanskar sub-basin.

Eastern Karakoram

The Karakoram Range is a NW-SE trending orogenic belt extending within Hunza and northern Ladakh area of Jammu and Kashmir. Geologically it comprises two different facies of rocks the one in the north representing sedimentary formations and the other in the south, a metamorphic facies and these two are separated by Axial Granite Batholith. The oldest fossiliferous formation is Late Carboniferous, which is referred as the Shaksgam Formation in the Western Karakoram and as Saser Brangsa Formation in the Eastern Karakoram (Fig. 6.13). The older metamorphic facies is called Pangong Tso Formation of schists, gneisses, marbles and metabasics. These are exposed in the Saser Mustang range and along the Shyok river bed. The age of this formation is uncertain and could be Precambrian to Silurian.

Saser Brangsa Formation: It comprises thinly laminated argillite, interbedded with impure dark grey limestone and calcareous sandstone, dark

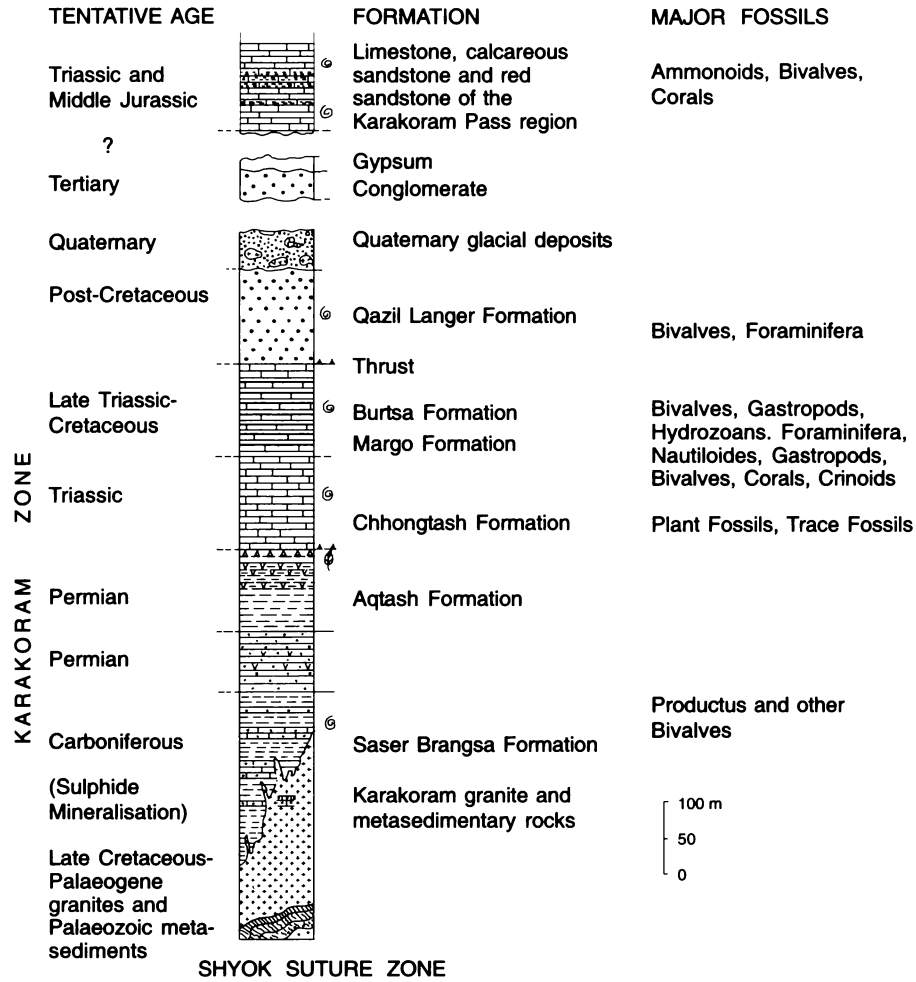


Fig.6.13. Schematic tectonostratigraphic traverse column of eastern Karakoram (Sinha et al. 1999) (source: Upadhyay, 2002).

grey greywacke. Black slates occur at the contact between Saser Brangsa Formation and the underlying Pangong Tso Formation. Saser Brangsa Formation has yielded *Spirifer, Costispirifer, Atrypa, Linoproductus, Fenestella* and on the basis of this assemblage it is assigned Late Carboniferous age.

Himachal Pradesh

A group status is given to the Carboniferous strata in the Spiti-Kinnaur sub-basin and designated as Kanawar Group, which includes Lipak, Po and Ganmachidam Formations.

Lipak Formation: Due to its dark colour, in contrast to the underlying

white Muth Formation and the overlying shale-dominated Po Formation, it can be easily identified in the fully developed sections. Originally Hayden proposed the name after a valley of this name. It comprises of dirty white to grey, locally cross-bedded sandstone in basal part, grey to ash grey shale interbedded with limestone and sandstone in the middle part and limestone, local shale and lenticular gypsum bed in the upper part. The formation has an uneven distribution throughout Spiti. In the Kinnaur area, this formation or its equivalent is not developed, but further southeast in the Kumaun area, similar rocks are referred to as "Kali Series." It has, however, considerable thickness towards northwest and in the Lahaul area. Sills of dolerite occur in the Lipak Formation at Tariya, Shalkar and WNW of Yulong Dogri.

The presence of limestone, dolomite and gypsum suggests an evaporite sequence. Change from the clastics of the Muth Formation to heterogeneous carbonate-dominated sequence together with hard grounds (surfaces of unconformity) and reefs indicate a relative deepening of the basin. The environment of sedimentation of Lipak Formation varies from sub-tidal to intertidal, with acquisition of supratidal conditions in the terminal part to form an evaporite basin, when gypsum was precipitated.

The basal Lipak contains *Cyathophyllum* sp., *Idiostroma, Atrypa aspens, Orthothetis* and *Productella.* Other important fossils are: *Syringothyris cuspidata, S. lydekkeri, Neospirifer banbadhurensis, Productus.* Besides these fossils are crinoids, corals, gastropods, echinoid spines, shell-hash – all these also form carbonate builders in some places. Also reported are conodonts of Tournaisian age from the Lahul area. The presence of *Tentaculites* and *Syringothyris cuspidata* in the basal part and *Phillipsia* cf. *cliffordi* in the upper part indicates a Late Devonian to Early Carboniferous age (Tournaisian) for the Lipak Formation.

Po Formation: This is also named by Hayden after a village of the same name. It is mainly developed in the NW and SE corners of Spiti valley. It is entirely absent in eastern Kinnaur.

The Po Formation forms a stepped topography due to alternation of light coloured quartzite and dark shale. It has conformable contacts both with the underlying Lipak Formation and overlying Ganmachidam Formation. It comprises alternation of dark grey, pale green shale, siltstone and white and grey sandstone, with shale predominantly in the middle part of the sequence. The strata have burrows, sole marks, ripples and some with internal erosion surfaces, besides occasionally low-angled festoon cross-bedded clean quartz arenite. This shale-quartz arenite cycle is repeated five to six times.

In the basal part of the Po Formation plant fossils *Rhacopteris ovata* and *Sphenopteridium fucillatum* have been recorded near Tabo. The *Rhacopteris*

flora represents the oldest undisputed megascopic land plants known from India. It is a cold climate flora.

The upper part of the Po Formation contains a rich assemblage of bryozoa *Fenestella*. Other fossils include *Productus lineatus, P. sabriculus, Dielasma, Reticularia lineata, Protoretepora ampla.* The trace fossils are represented by *Asteriacites, Aulichnites, Cochlichnus, Gyrochorte, Phycodes, Planolites, Skolithos, Ruzophycus* and *Rhizocorallium.* Besides, the shale in the Mardang nala section contains nautiloid, orthoceratid, *Fenestella, Pleuratomaria* and crinoids. Though based on plant remains, a Middle Carboniferous age to Po Formation was assigned. The overall invertebrate fossil assemblage suggests a Lower to Middle Carboniferous age (Late Tournaisian to Serpukhovian).

Ganmachidam Formation: This formation, earlier referred to as Permian Conglomerate by Hayden, is developed only in those sections where Po Formation is also developed. This has a gradational contact with the underlying Po Formation, best exhibited in Kurig, Yelong valley, Po, Pomarang, Angla and other sections. The upper part of its contact with the overlying Gechang Formation of the Kuling Group is very sharp. It comprises pebbly mudstone, pebbly siltstone, pebbly sandstone, conglomeratic sandstone and black shale alternations. The lithounits are lenticular in nature with the result that even in close by areas the lithostratigraphic assemblage varies. There is coarsening of successive cycles indicating a sequence from shore facies to beach and possibly deltaic in some cases. The conglomeratic parts are perhaps the remnants of mountainous coastal rivers, reworked on a beach.

The entire sequence is unfossiliferous. The conformably underlying Po Formation is not younger than Middle Carboniferous and hence the lower age of the Ganmachidam Formation may be Middle Carboniferous. It is overlain by a sharp contact, denoting a possible break, by the Asselian-Sakmarian Gechang Formation of the succeeding Kuling Group. The upper age limit of the Ganmachidam Formation thus may be Upper Carboniferous possibly transgressing into earliest Permian.

Uttarakhand

In Uttarakhand, the Kanawar Group represents the Carboniferous with the following succession:

Kanawar Group	Po:	Kali river section: very thin Fenestella Shales (Middle Carboniferous)
	Lipak:	Gunji, Kalapani and Kuti in the Kali valley (Early Carboniferous)

The fossils are generally similar to those reported from the Lipak and Po Formations in the Spiti area.

PERMIAN

In Peninsular India, after a great hiatus since the Precambrian, terrestrial deposition commenced, generally with pockets of glacial tillite of Upper Carboniferous age followed by deposition of terrestrial strata of the Gondwana Supergroup, extending almost to Lower Cretaceous. In the Himalayan terrain, however, after the Muth Quartzites of Devonian in some places and those of Lower Carboniferous in others, particularly in Kashmir, Spiti and Kumaun, there was a hiatus. Land conditions prevailed followed by the earliest manifestations of volcanism during Upper Carboniferous (?), but the outpourings were considerable, though intermittently during the Permian. This is seen in the Pir Panjal Range. Intercalated with these volcanics are fossil plant beds.

Extensive marine sedimentation is a conspicuous feature in the Himalayan terrain in Permian in Jammu and Kashmir [extending right from Asselian to Tatarian (Table 6.3)], in Ladakh and Eastern Karakoram, in Himachal Pradesh particularly in Lahaul, Chamba basin and Spiti, in Uttarakhand, Bhutan

Table 6.3. Permian in Kashmir faunal zones (modified after Nakazawa and Kapoor, 1977)

248 Ma Greisbachian? Tatarian	Khunamuh Fm. Zewan Fm.	E D C B A	*Claria bioni* *Neogondolella subcarinata* *Cyclolobus, N. subcarinata* - *Colaniella minima*, Ahadehell	
Ulfimian - Kazanian - - - - - -	Permian Gondwana	Panjal Volcanics	Mamal beds ? Mund beds ? Marahoma beds Vihi beds Nishatbagh	In Peninsular India
Artinskian - Kungurian - - - - - -	Agglomeratic Slate	Pyroclastic Division	II Volcanic Flow *Buccanopsis wartha* zone *Praeundulomya Spirifer* zone *Taeniothaems-Buxtonia* zone I Volcanic Flow	- - - - - - Umaria Fm. - - - - - -
Sakmarian - - - - - - Asselian 290 Ma		Diamictite Zone	Barren *Eurydesma Deltopecten* zone *Fenestella* zone	 Manendragarh Formation

and Arunachal Pradesh. There are marine incursions of Permian within Peninsular India also prominently noted in Rajasthan, Madhya Pradesh and Bihar.

Jammu and Kashmir

The upper part of the Agglomeratic Slate at the base of the Panjal Volcanics contains the following fossil zones:

The lower Fossil Zone contains *Eurydesma cordatum* (Plate 6.3-1&2), *Deltopecten mitcheli, Megadesmus gracilis* and *Aviculopecten cuneatus*. This assemblage is considered to be Early Asselian in age.

The upper Fossil Zone contains *Derbyia, Buxtonia kashmiricus, Taeniolthasrus permixtus, Fusispirifer plicatus, Cyrtella, Reticularia, Brachythyris*, and *Wyndhamia*. This assemblage is considered to be of Sakmarian-Early Artinskian in age.

Panjal Volcanics: The rocks of this group are prominently visible on the summits and sides of Pir Panjal Range forming hill masses. The entire crest of the Pir Panjal Range and the southwestern slope extending from Pir Panjal Pass in the northwest to Kaukut peak (13480' or 4109 m) in the south-east is formed of this group. The Trap lies on top of Agglomeratic Slate and almost forms the central axis of the Pir Panjal Range, where it attains a maximum thickness of about 1000 m. It is a conspicuous Palaeozoic lithounit covering nearly 775 km^2 in the Kashmir valley constituting over 20% of the exposed hard rocks. A fine section of the Panjal Trap is seen in the gorge of Mandi valley between Sekhulu (33° 7': 74°15') and Mandi (33°48': 74°15') where about 700 m of steeply dipping bedded flows are laid bare in the precipices.

Panjal Volcanics are directly overlain in many parts by a series of beds of cherts, siliceous shales, carbonaceous shales, thin-bedded limestone, flaggy siliceous beds of quartzite with a band of rock known as 'novaculite.' These beds contain fossil impressions of ferns like *Gangamopteris* and *Glossopteris*, equisetales, conifers with skeletons of labyrinthodonts and fishes. These beds are met with in several localities. Both the exposures at Risin and Zewan in the Vihi district are the most noteworthy because of their being overlain directly by the fossiliferous Permian strata.

The Panjal volcanic episode represents continuous outpourings of lava flows without any noticeable time lag as inferred by fused nature of flow contacts and conspicuous absence of weathered zone at the top part of the flows, prior to outpourings of succeeding flows. The volcanics consist of basaltic andesite with typical glomeroporphyritic texture, andesite with minor dacite and basaltic-

andesite and andesite composition. Field studies reveal as many as 156 flows totalling to 2414 m in the Sonamarg sections. The Panjal volcanics show close similarities in nature and composition of flow in these widely separated sections. The nature of the volcanic flows is indicated by 3 to 10 in the Fig.6.14. The episode signals the outpouring of the flows with little time lag in terrestrial as well as sub-aqueous environments.

A two-fold classification of the Panjal Volcanics into Lower and Upper not only holds good throughout the northwestern Kashmir but also in the

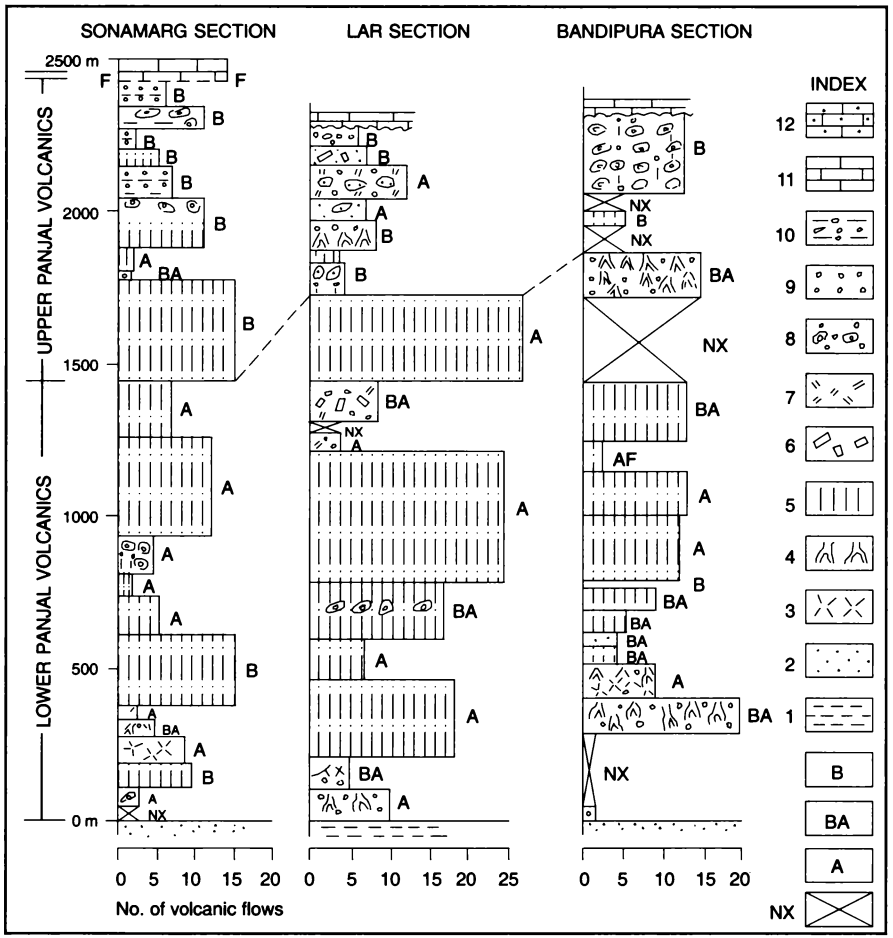


Fig.6.14. Lithocolumn of the Panjal Volcanics of Sonamarg, Lar and Bandipura sections of northwestern Kashmir. **1** - Cambro-Silurian: Slate, siltstone, quartz arenite; **2** - Agglomeratic Slate: Slate, quartz arenite, diamictite and tuffaceous rocks; **3-10**: Panjal Volcanics: **3** - Glomeroporphyritic flow, **4** - Pipe amygdule/vesicular flow, **5** - Compact part of flow, **6** - Porphyritic flow, **7** - Weathered flow, **8** - Volcanic breccia, **9** - Vesicle/ amygdule, **10** - Schistose flow; **11** - Zewan Formation: Limestone, carb. shale; **12** - Middle Triassic: Limestone and shale: **B** - Basalt, **BA** - Basaltic andesite, **A** - Andesite, **Nx** - no exposure; **F** - Fault (after Inder Singh, 1996).

southwestern Kashmir (Awantipura, Tral and Lidder Valley) where 400 m thick intervening acid differentiates are also observed.

The flows in the lower Panjal Volcanics vary in thickness from 2 to 46 m, but are mostly around 10 m. The flows are usually non-porphyritic in nature but a group of 8-10 glomeroporphyritic flows with radiating clusters of plagioclase laths is quite conspicuous in all the sections occupying the basal part of the sequence. The vesicles in the flow vary from less than 2 to 50 mm across and are spherical, ovoid to elongate in shape with irregular margins. These vesicles are often filled with secondary chlorophaeite, chlorite, epidote, quartz and calcite.

The upper Panjal Volcanics are dominantly basalt to basaltic andesite and subordinate andesitic flows. These flows vary in thickness from a metre to 44 m with an average of 13 m. The basaltic flows are dark greenish grey, fine to medium-grained, compact, non-porphyritic and usually accompanied by the top part having angular to subangular vesiculated, epidotised volcanic fragments cemented by cherty matrix. The acid varieties found in the area around the Kashmir valley include rhyolites, dacites and trachytes.

Panjal volcanics possibly represent island arc tholeiitic volcanism in bimodal environment i.e. in terrestrial as well as subaqueous conditions. The intense epidotisation in the amygdaloidal part of the flows, besides few pillow lavas from Guruyal ravine, support marine environment of deposition.

These are overlain by Zewan Formation (Middle to Late Permian). However, the Gondwana plant beds (Early Permian) are also known to overlie these volcanics in some sections in Kashmir. These may suggest that Panjal Volcanics may represent time transgressive episode spanning from Artinskian to Kungurian.

Permian Gondwana/Gangamopteris Beds: The Permian Gondwana Beds, a term earlier preferred by some to the name of the Gangamopteris Beds, are variously named according to different horizons in which they occur within the Panjal Volcanics as Mamal, Munda, Marahoma, Vihi and Nishatbagh Beds. These are shown in the Table 6.3.The possibility of discontinuity between the Zewan and the Permian Gondwana has been suggested, though in Pahalgam, the Mamal Beds are in conformable contact with the Zewan. The Permian Gondwana Beds are considered to have been deposited near the contemporary shoreline, and in some places are littoral or coastal or lagoonal and in other places estuarine or even fluviatile. These are met with on the south side of Pir Panjal Range overlying Agglomeratic Slate unconformably. In Golabgarh Pass-Didom Gali (12501' or 3810 m) area, and also in Bhadarwah-Bhallesh sub-basin, and on the northeastern flank of the Warwan valley anticline, these occur below the Zewan Beds.

Five distinct floras were recognised above the Carboniferous beds, one below the Panjal Trap and the rest above it.

1. Below the Panjal Trap: Nishatbagh Bed – It marks the beginning of Gondwana in Kashmir and occurs as isolated outcrops at various localities of which Dal Lake, Basmai, Nagmarg, Bren and Nishatbagh are important. *Gangamopteris angustifolia, G. kashmirensis, Glossopteris angustifolia, G. indica, Psygmophyllum haydeni, Cordaites hislopi, Samaropsis, Cordaicarpus* and stems.
2. On the top of Panjal Trap: Vihi Bed. (Gangamopteris Bed). *Gangamopteris kashmirensis* (dominant), *Vertebraria* sp., *Psygmophyllum haydeni*, cones and stems of lycopods.
3. Marhoma Bed: Lava between this and Vihi Bed. *Schizoneura gondwanensis, Spenophyllum, Sphenopteris polymorpha, Glossopteris communis.*
4. Munda Bed: Traced from Jawahar tunnel to Ahrbal. *Pecopteris, Taeniopteris kashmirensis, T. feddeni, Vertebraria indica.*
5. Mamal Bed: Youngest floral bed of Permian Gondwana in Kashmir. *Lepidostrobus kashmirensis, Schizoneura, Phyllotheca, Pecopteris, Glossopteris indica.*

The Gondwana affinity of Permian floral beds is undisputable in spite of its having distinct nature, being far from the mainland. The fact of its being a part of the Gondwana continent gets the support from the underlying *Eurydesma* fauna, typical of the Gondwana shelf.

Zewan Formation: Marine fossiliferous rocks of Permian age, referred to as Zewan Beds in Kashmir stratigraphy, are well exposed in Zewan village in Vihi district. This locality represents a type section for the Permian and here the Gangamopteris Beds are directly overlain by a thick series of limestones and shales, rich in fossils.

In the Jammu region, the only important occurrence is that of Didam Gali – Golabgarh Pass area, where a syncline of Panjal Volcanics encloses a succession of Gondwana Formation, Zewan and Trias. Here the siliceous and carbonaceous slates containing Lower Gondwana flora are succeeded by the Zewan Formation comprising an earthy, calcareous sandstone and shale with brachiopods, dark thinly bedded limestone with *Protoretopora ampla*, and about 1000 m of Productus Shale. The Zewan in turn is succeeded by Triassic Limestone, which forms the core of the syncline. Fossiliferous Permian strata overlying the Panjal Volcanics and Gondwana beds occur in Bhadarwah-Bhallesh sub-basin also. The base of this formation is argillaceous and contains remains of *Protoretopora,* a polyzoan resembling *Fenestella.* The upper part is

calcareous with intercalations of shale containing fauna, having affinities with the Gungri Formation (Productus Shale) of Spiti. The Zewan Formation is also reported from the hills southwest of Vihi, Pir Panjal, Upper Sind and Lidder valleys.

Brachiopods: *Leptodus, Costiferina, Cancrinella, Waagenoconcha, Spirigerella, Stenocisma, Whitspakia, Marginifera, Neospirifer, Productus cora, Spirifer rajah*
Ammonoid: *Cyclolobus walkeri*
Conodonts: *Hindeodus minutus, Gondolella carinata*

Khunamuh Formation: The main constituents of Unit E (*see* Table 6.3) at the top of the Zewan Formation are dominantly Permian brachiopods much reduced in size, abundant bivalves (many genera, more than brachiopods), foraminifers, and bryozoans almost nil. Among bivalves *Claria bioni* Nakazawa is significant and present throughout the unit. The genus is a common characteristic fossil of Early Triassic and as such the unit indicates a dubious nature. Brachiopods and some bivalves indicate a Permian age, while *Claria* and other bivalves, a Triassic age. This unit, on this account was suggested to be a zone of mixed fauna with its age as Early Greisbachian i.e. the first appearance of Triassic bioelements.

In Ladakh, the Zanskar range exposes an excellent section of upper Palaeozoic rocks of the Spiti-Zanskar sub-basin. The formation is interbedded with basic lava flow representing the Phe (Panjal) volcanic activity in the area. In the northwest part of Spiti-Zanskar sub-basin in Ladakh there is a major transgressive event of the Phe Volcanics over the early Palaeozoic-Proterozoic sediments.

The Phe Volcanics appear continuously from the Gurloke nala of the Lingti valley in the southeast to the mountain slope near Uldok in the Ringdom Gompa area in the northwest. The Phe Volcanic belt constitutes a very conspicuous lithological unit along the southern escarpment face of the Zanskar Mountains flanking the northern part of the Lingti, the Phise, the Kurgiakh, the Doda and upper reaches of the Suru river.

In Kurgiakh Chu and Linti valley, where a complete sequence of Proterozoic to Mesozoic rocks is exposed, the Phe Volcanics occupy a normal position between the Ganmachidam Formation of the Kanawar Group and the Kuling Formation. But further northwest, the volcanics progressively overlap successively on to older formations, ultimately resting on the Giambal Group in the Ringdom Gompa sector. Thus the base of the Phe Volcanic belt in the northwest half of the Zanskar area is a marked angular unconformity.

The Phe Volcanics, as a linear volcanic belt, comprises a pile of compound lavas of 250 to 500 m thickness. It comprises of 9 to 10 major flows and several minor flows. As the Phe Volcanics occurs between the Ganmachidam Formation (Carboniferous) and the Kuling Formation (Permian), it is suggested that the volcanic activity commenced at the close of Carboniferous and ceased during Early Permian (Sakmarian stage).

The succeeding Kuling Formation is exposed in the section between east of Mulbekh and Lamayuru and it occurs in close association with the Lilang Group (Trias) in an extremely complicated schuppen belt bounding the southern margin of the Indus Tectonic Zone. These were described as 'Indus Flysch,' but a study of the lithology seems to contradict such an inference as they are mainly made up of carbonaceous shales-slates, often bleached to ash grey or pale brown colour with thin-bedded limestone, calcarenite and sporadic phosphatic nodules, thin-bedded siltstone and silty shale. At many places, mud cracks and worm burrows are noticed in shales-slates. *Cyclolobus* sp. from the area close to Honiskot, and also other Permian fossils from Lamayuru, besides Permian Productids, *Polypora* sp., and crinoidal stems, confirms the age of these rocks to be Permian.

The Kuling Formation along the Indus Tectonic Zone is considered to be part of the Spiti-Zanskar Tethyan belt forming the northeastern limb of the Spiti-Zanskar synclinorium.

In Eastern Karakoram, the Saser Brangsa Formation is reported to be overlain by a sequence of siltstone, coarse-grained sandstone and black shale interbedded with pillow lavas having interstratified limestone. The limestone has yielded a faunal assemblage of *Parafusilina, Pseudofusilina* and *Schwagerina* (foraminifera). On the basis of this assemblage it is assigned an Early Permian age. It is substantiated by the occurrence of the Early Permian plant fossils of *Noeggerathiopsis* and *Gangamopteris equisetalean.* This is named as Chhongtash Formation. Below this lies Aqtash Formation comprising a 500 m thick succession of polygenetic conglomerate, purple and green shale, limestone, chert lenses and volcanics. It is highly folded and is in faulted contact with the Saser Brangsa Formation. On the basis of the occurrence of fusilinids and corals an Early Permian age is assigned to the Aqtash Formation.

Himachal Pradesh

In southwestern Lahaul, along the southern slope of the Dilburi Ridge and along the northern slope of the Pir Panjal Range forming the southwestern flank of the Chandra and Chandra Bhagha valley is the Tandi belt. It is a highly folded, predominantly carbonate sequence resting over the carbonaceous phyllite and quartzite lithounits of the Terminal Proterozoic Batal Formation

of the Haimanta Group. The Tandi Group is divisible into Kukti, Gushal and Dilburi Formations in the ascending order.

Kukti Formation is made up of carbonaceous phyllite, thin-bedded limestone, calcareous phyllite, and sporadic calcarenite and pebble beds. *Michelina salinaria, Waagenophyllum indicum, Wentzellella* cf. *salinaria* and *Cyclolobus oldhami* (Plate 6.3- 8&9) are reported from this formation. The last fossil confirms the age of this formation as Late Permian.

In the Chamba sub-basin, between the Pir Panjal and the Dauladhar Range of NW Himachal Pradesh, a thick sequence of Proterozoic and Upper Palaeozoic-Mesozoic formations is exposed. These formations link up with similar rock types of Bhadarwah in Jammu and Kashmir in the northwest and the Proterozoic rocks are the continuation of similar rocks of southern Lahaul. The sequence in the Chamba area is made up of Chamba Formation (Meso-proterozoic), Manjir Formation (Neoproterozoic), Batal Formation (Terminal Proterozoic), Salooni Formation (Permian) and Kalhel Formation (Triassic).

Salooni Formation comprises black shale, slate, calcareous slate and lenticles of limestone. *Modiola lidarensis, Spiriferella rajah, Productus* sp. are some of the fossils found in Salooni indicating Permian age. In the basal part are basic lava flows, which may be correlatable with the Panjal Volcanics of Jammu and Kashmir.

In the Spiti area, the term Kuling is restricted to the sequence between the Kanawar Group and older formations below and the Lilang group above. The base of the Kuling Group marks a major unconformity of regional significance. It variously overlies the Thango, the Takche, the Muth, the Lipak, the Po and the Ganmachidam Formations. As the Kuling sedimentation heralds the advent of Permian, it, along with its equivalents in the Tandi and Chamba areas, represents a major transgressive phase in the Tethys Himalayan Tectogen and has a wide regional significance in the Indian subcontinent. The Kuling is now raised to the status of a Group (Bhargava and Bassi, 1999) and is divided into Gechang and Gungri Formations.

Gechang Formation: Its best sections are in the Lingti valley around Lalung village, along the left bank of the Spiti between Poh and Tabo, Khimokul La and in Ratang valley. The Gechang Formation comprises brown to grey, pale grey, coarse-grained weakly bioturbated cross-bedded, calcareous sandstone with local conglomerate and/or shell lag at base. Locally, mud cracks are observed in the upper part.

Apart from some trace fossils, *Eurydesma cordatum, Deltopecten, E. hasdoensis, E. manendragarhensis, Waaganophyllum* and *Neospirifer* are also reported.

The lithounits of the Gechang Formation, beginning with conglomerate

or shell lag, indicates a transgressive cycle. Shale layers and micaceous sandstone in the middle part point to subtidal environment of sedimentation, which changed to foreshore to upper foreshore in the upper part when ferruginous sandstone was deposited and mud cracks were formed. *Eurydesma* in the basal part and *Waagenophyllum* near the top suggest an Asselian to Sakmarian (Lower Permian) age for the Gechang Formation.

Gungri Formation: This formation is uniformly developed in Lahaul, Spiti and Kinnaur and like the Muth Formation forms an excellent marker bed. The Gungri Formation, abruptly resting over the Gechang Formation, comprises black shale, calcareous silty shale, phosphatic cherty calcareous nodules, and thin limestone and coquina lenses. Some of the nodules enclose fossils. Towards the upper contact, the Gungri Formation is overlain by a ferruginous layer, which has been interpreted to represent a subaerial break and by some as subaqueous break. This formation represents sedimentation chiefly of shelf and under restricted circulation. Fine shell fragments and silty layers represent storm layers.

Zoophycos is a common trace fossil in the Gungri Formation. The other fossils include *Marginifera himalayensis*, *Productus gangeticus*, and *Spiriferella rajah*. The cephalopods are *Xenaspis carbonaria* and *Cyclolobus oldhami*. This assemblage suggests a Djulfian age – possibly extending into a part of Dorashamian or Changsingian (uppermost Permian). Kungirian and Midian elements (middle Permian) have not been so far encountered between Gechang and Gungri Formations. This absence could be due to a break in sedimentation, manifested by sharp contact between the Gechang and Gungri Formations.

Uttarakhand

In the Tethys Himalaya, an 18 m thick sequence occurs over Muth Quartzite in Niti, Malla Johar and Byans. These contain *Linoproductus – Waaganoconcha* assemblage of Sakmarian age (Early Permian). In the Niti Pass, Hotigad and Raulibagar sections are exposed rocks of Kuling Shale Formation. These contain striate bisaccate pollen. These palynoflora show a close similarity with the contemporaneous palynoflora of the Raniganj Formation of the Gondwana Supergroup. Besides, both the Kuling Formation and the Raniganj Formation have a common characteristic of having a few elements of Lower Permian (namely *Plicattipolenites* and *Callumispora*) which, if not considered as reworked, may be taken as remnants of the older floras from Early Permian. The palynoflora here can be taken as precursors of Early Triassic microflora in Niti valley.

In the Lesser Himalaya, the Boulder Slate of Doggada and adjoining area

of Garhwal, are similar to the Agglomeratic Slate of Kashmir, and contain *Fenestella garhwalensis, Polypora middlemissi, Dogaddanella audeni* (bryozoa), *Aviculopecten* (pelecypoda), *Spiriferina, Neospirifer, Productus*, and *Strophalosia* (brachiopod) of Early Permian. The Late Permian fauna of *Dielasma latouche, D. kinauricum, Spriferella rajah, Spirifer, Marginifera* (brachiopod) and *Cyclolobus oldhami* (cephalopod) are also reported from the area.

The litho- and chronostratigraphic correlation of Phanerozoic sequence in Tethyan belt of NW Himalaya is presented here as suggested by Arora et al. (2002) in Fig.6.15. The nomenclature of a few formations may, however, be debatable, as they are not defined as per the code of stratigraphic nomenclature.

Bhutan

Seti Khola Formation: Two northward dipping thrusts separate 1000 m thick Seti Khola Formation from the underlying Siwalik sediments in the south and the overlying Phuntsholing Formation in the north. The formation is divisible into the following horizons:

A. Pink, maroon, white, sporadically green, well-bedded sandstone. Red beds are the dominant unit – 400 m
B. Rhythmically interbedded carbonaceous black, grey and green shale and calcareous quartzwacke – 140 m
C. Dirty white to grey sandstone, carbonaceous shale and diamictite – 550 m.

Horizon C contains marine fossils represented by bryozoans, brachiopods, gastropods and crinoids, which come from four different levels. They contain *Neospirifer* cf. *fasciger* (Keyserling), *Trigonotreta* sp., *Platyteichum* sp., *Protoretopora* cf. *ampla, Waaganoconcha* cf. *vagens* and *W.*cf. *humboldti*, which indicate a late Early Permian age. A shallow marine to lagoonal environment is suggested for the sediments of the formation based on lithology, sedimentary structures and fossil content.

Seti Khola Formation of Bhutan Lesser Himalaya is correlatable with Garu Formation of Arunachal Pradesh in the east and Rangit Pebble Beds of Sikkim in the west. Recognition of the Permian Seti Khola Formation from the Sankosh valley in Bhutan establishes the presence of a more or less continuous marine Permian sequence along the foothills of the Himalaya.

Arunachal Pradesh

Arunachal Himalaya remained a landmass where no sedimentation took

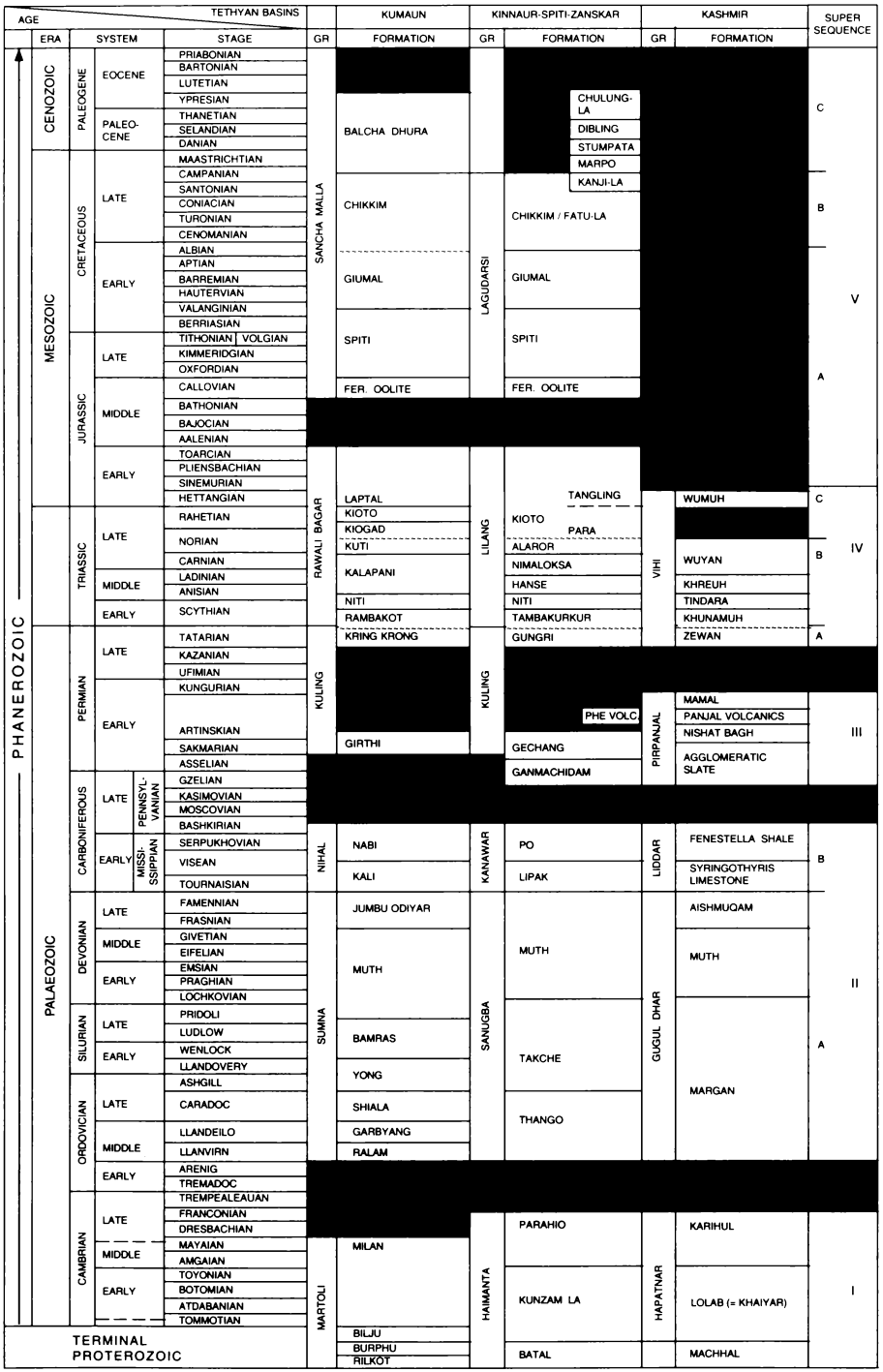


Fig.6.15. Litho- and chrono-stratigraphic correlation of Phanerozoic sequence, Tethyan belt, Northwest Himalaya (source Arora et al. 2002).

place from Neoproterozoic to Carboniferous. The Palaeozoic is represented by two sedimentary sequences, the Lower Permian rocks of the Lower Gondwana Supergroup and the Upper Permian of the Yamne Formation.

Lower Gondwana Supergroup: This lies unconformably overlying the Bomdila Group (Middle to Late Palaeoproterozoic) abutting against the Main Boundary Fault. This occurs in an undulating ENE-WSW direction from the border of Bhutan, crosses the Subansiri river, and then takes a turn towards north up to Sisang river, limited in the east by the Bame Fault. Lithostratigraphically, the sequence is divisible into Miri, Bichom (also named as Bomte, Garu and Rilu Formations in different places), Bhareli and Abor Volcanics in ascending order. Divisions based on facies and tectonics have also been attempted.

Miri Formation overlies unconformably Ketabari and Tenga Formations of Palaeoproterozoic and is conformably overlain by Bichom Formation. The Bichom Formation is divided into the Rilu, Bomte and Sensa members. The Bomte Member contains a rich marine Early Permian fauna.

Brachiopods: *Subansiria naganensis, Lissochonetes carbonifera, Dielasma dadanese, Linoproductus cora, Oldhamina* sp.
Pelycypods: *Anthraconeilo kansana, Eurydesma cordatum, Phestia* cf. *P. lyonesis, Deltopecten mitchelli, Aviculopecten* sp.
Gastropods: *Warthia* cf. *intermedia, Platyeichum brenensis* (Reed), *Bellerophon* sp., *Pleurotomaria* sp.
Cephalopods: *Uraloceras siangense, Sueroceras bomtense.*
Bryozoans: *Fenestella* spp., *Polypora* spp., *P. megastoma.*
Conulariida: *Conularia laskari*

The fauna and microfloral assemblage indicate a cool palaeoclimate during the deposition of the Rilu and Bomte Members. The presence of coal balls within the Bomte Member is suggestive of deposition in shallow marginal swamps subjected to marine incursions.

The Bahreli Formation constitutes the continental sedimentation of the Lower Gondwana sequence and conformably overlies the Bichom Formation. It comprises a thick sequence of grey to dark grey feldspathic sandstone and grey to black carbonaceous shale with lenticular coal beds. The plant fossils recorded are as follows:

Upper Member: *Schizoneura gondwnensis, Vertebraria indica, Phyllotheca* sp., *Cordaicarpus zeilleri, Samaropsis* sp. *Glossopteris longicaulis, G. indica.*
Lower Member: *Gangamopteris* cf. *cyclopteroides, Glossopteris* sp. *Vertebraria* sp., scales of *Glossopteris* sp.

The palynoassemblage dominated by the occurrence of *Callumispora* in association with radial monosaccate pollen grains is suggestive of Early Permian age comparable to the palynoflora in the lower part of Karaharbari Formation of Peninsular Gondwana.

Abor Volcanic Formation: The name given by Coggin Brown has been used to describe mafic volcanics and the associated inter-trappeans in the Liang valley, which have now yielded Lower Permian microflora. The Abor Volcanics are considered coeval with the Lower Permian Panjal Volcanics of northwest Himalaya. The volcanic rocks comprise basalt, andesite, acid tuffs, lapillis and agglomerates. The basalts and andesites occur as highly amygdaloidal, 5-10 m thick flows having greenish base and reddish coloured top and are best exposed in the road section around Dosing, along Pangin Geku – Yinkiong road. Development of pillar structure is also seen. The rocks are aphanitic and predominantly non-porphyritic. In thin sections, the groundmass in both the types show extremely fine-grained intersertal to intergranular texture. The minerals in the groundmass are plagioclase, augite, chlorite, iron oxides (magnetite), epidote, sphene, glass, calcite and rarely pumpellyite. Geochemically the rocks are transitional between alkali basalt and tholeiite.

The inter-trappeans near Yinkiong comprise conglomerates, calcareous sandstone and carbonaceous sandy shales. The shales have yielded many palynomorphs. A band of black shale in an inter-trappean quartzite-shale (3 m) (from Yambung nala to Roting) has yielded Lower Gondwana sporomorphs.

Yamne Formation: This sequence is of very restricted and localised nature reported from the southern slopes of Dalbuing in the Yamne nala and hence the name. It is sandwiched between the underlying Geku Formation yielding Early Eocene plant fossils and the overlying Dalbuing Formation containing Lower Eocene marine Nummulitic fauna. It comprises pale brown ferruginous shale about 5 m thick and contains marine invertebrate fauna of Upper Permian age. Both the contacts appear to be tectonic as evidenced by shattering, plications and contortions in beds. The fauna include the following:

Bivalves:	*Aviculopecten, Burmesia, Eoschizodus, Etheripecten, Goniopora, Mysidioptera.*
Brachiopods:	*Neochonets, Neospirifer, Productus, Spirifer.*
Gastropods:	*Loxonema, Meekospira, Mourlonia, Neilsonia.*

Peninsular India

Marine incursion in the southern belt of Himalaya in the Early Permian

took place possibly through rift valleys in the Indian Shield. Marine incursions are reported from a few places in Peninsular India as well. These together with that in Salt Range (in Pakistan) throw light on the palaeogeography of Central India during part of the Permian period and aid in precise correlation of associated terrestrial sediments in those areas (Fig.6.16).

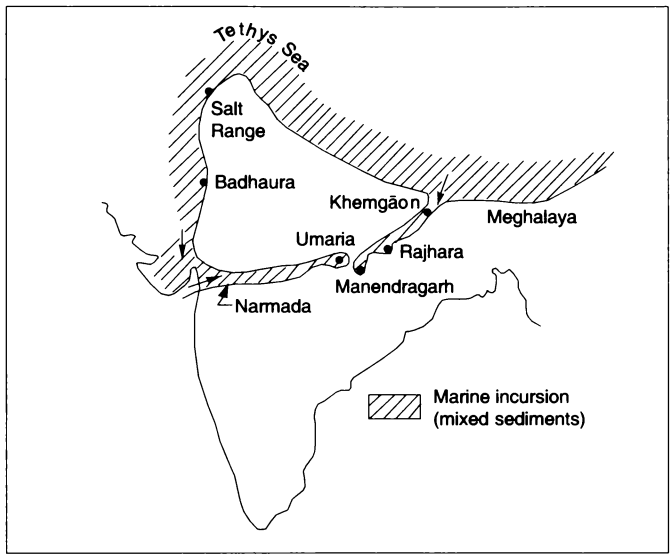


Fig.6.16. Marine incursion in southern belt of the Himalaya in the Early Permian took place possibly through rift valleys in the Indian Shield (after Chatterjee and Hotton, 1986) (source: Valdiya, 1997; from Gondwana Research, v.1, p.6; © International Association of Gondwana Research).

Salt Range, Pakistan: A boulder bed of glacial origin of a maximum thickness of 60 m overlies unconformably the Cambrian. These seem to be similar to the Talchir Boulder Bed at the base of many Gondwana basins in Peninsular India. Immediately above the boulder bed occurs a Eurydesma horizon containing many bivalves (*Eurydesma cordatum, Nucula, Aviculopecten*), brachiopod (*Dielasma dadense*) and bryozoa (*Fenestella fossula*). This is correlatable with the Eurydesma horizon in Kashmir. Overlying the Eurydesma horizon is the (pteropod) Conularia zone (*Conularia laevigata, C. punjabica*), and gastropod *Pleurotomaria* along with a few lamellibranchs and brachiopods. These are considered to be uppermost Carboniferous (Uralian – above Gzhelian) to Lower Permian age.

Badhaura, Rajasthan: The marine exposures here among others, contain *Polypora ampla, Dielasma, Spirifer, Bellerophon, Conularia* cf. *laevigata.* Similar fossils are reported in the nearby locality of Bhimjikagaon. The fauna

show close resemblance to the Conularia and Amb fauna of the Salt Range indicating Upper Sakmarian to Artinskian age. Besides this the common elements between the faunas of Badhuara and Umaria are noteworthy.

Umaria, Madhya Pradesh: About 3 m-thick marine strata occurs intercalated in the Lower Gondwana strata in the Narsarha railway cutting near Umaria in Madhya Pradesh. Similar intercalations occur at Anukpur and Manendragarh about 150 km ESE of Umaria. The Umaria marine bed overlies the Talchir Boulder Bed (of the basal part of the Gondwana Supergroup) and passes gradually into the overlying Barakar rocks of Lower Gondwana. In the marine bed, made of sandstones and clays, a number of species of the following genera are found – *Productus, Spiriferina, Reticularia*, and *Athyris.* A few gastropods (*Pleurotomaria umariensis*) were also met with in this assemblage, besides a bryozoan *(Rhombopora*). Crinoid stems and fish remains have also been reported from this bed. Productids form the predominating element of this assemblage. It is inferred that possibly an arm of the sea extended from the west (Fig. 6.16) up to this place and a little beyond leading to the deposition of these sediments during the Permo-Carboniferous times.

Manendragarh, Madhya Pradesh: A marine bed was discovered under the railway bridge on Hasdeo river, about 4 km southeast of Manendragarh railway station. This is just 5 m thick and is associated with the basal member of the Talchir Formation (of Lower Gondwana) overlying the Archaean. No marine fossils are reported from the upper members of the Talchir Formation, although its total thickness is about 50 m. The marine bed around Manendragarh commences with shale followed by conglomerate, blackish shale, green splintery shale, and an uppermost member of green sandstone. The fossils are mainly confined to the basal conglomerate horizon. Representatives of the genus Aviculopecten form the bulk of the fossils.

Pelecypod:	*Aviculopecten squamuliferous, A.mitechelli, Deltopecten, Eurydesma manendragarhensis, E. hasdoensis*
Gastropod:	*Euomphalus, Pleurotomaria*
Brachiopod:	*Trigonotreta, Spirifer*
Bryozoa:	*Protoretopora ampla*
Crinoid:	*Streblopteris*
Forams:	*Hyperammina, Glomospira, Trochammina, Tolypammina*

The marine fauna has close affinities with the Rajhara fauna of Bihar, Darjeeling fauna of West Bengal, Khemgaon fauna of Sikkim and Subansiri fauna of Arunachal Pradesh, thereby indicating that the marine transgression, which deposited the marine rocks at the base of the Talchir Formation came

from the north. On the other hand, the Umaria fauna, which lies close to Manendragarh, has affinities with those of Badhaura in Rajasthan and Salt Range from Pakistan, thereby indicating that the transgression of the sea, which deposited the marine rocks at Umaria, came from the west along the Narmada rift. These two arms of the sea apparently came at different times during the Early Permian period. It is believed that the Manendragarh marine transgression took place during Asselian, while that of Umaria occurred during Sakmarian period as indicated by their fauna. It may be noted that both the pathways suggested, one from the west and the other from the northeast, are along the Narmada-Son fracture zone and the incursions must have been aided by movement along these faults. It may, however, be mentioned that there are views different from this, namely that (i) the Umaria marine bed could be the result of a transgression from the southeast and (ii) the Umaria and Manendragarh beds form part of the same environment, but of different times.

A tentative correlation of the above marine Permian beds in Peninsular India is presented in Table 6.4. Palaeozoic seqeunces in many other sectors are provided in Table 6.5 (folder).

Table 6.4. Correlation of some marine Lower Permian Beds of India

	Kashmir	Salt Range	Rajasthan	Madhya Pradesh		Sikkim (Khem-gaon)	NEFA (Suban-siri)
				Umaria	Manendragarh		
Artinskian				Damuda	Damuda	Damuda	Damuda
		Katta beds *Amb beds* *Conularia Bed*	*Badhaura Fauna*	*Umaria Marine Bed*	Sandstones and shales	*?Product-tus* Zone	*Suban-siri Fauna*
Sakmarian	*Agglome-ratic Slates*	TALCHIRS *Eury-desma bed*	Sandstones & shales	Sandstones & shales	*Eurydesma Fauna*	*Eury-desma Fauna*	
	Boulder Bed	Boulder Bed	Boulder Bed	Boulder Bed	Boulder Bed	Boulder Bed	Boulder Bed

Note: Beds shown in italics indicate marine conditions (after Sastry and Shah, 1964, opp. p.142)

Cauvery Basin

From a well, Pundi-B, drilled in Cauvery basin (Thanjavur sub-basin in Tamil Nadu) about 10 km ESE of Thanjavur, a rich assemblage of radial monosaccate genera associated with Trilete spores and Leiosphaeridia suggestive of Early Permian age has been recorded (Asselian to Sakmarian). This is overlain unconformably by palynofossils of Turonian (Mid-Cretaceous age).

These assemblages show general similarity with other Talchir assemblage recorded from elsewhere like Goria, South Rewa basin, and Jayanthi coalfield, Bihar.

Volcanism and Magmatism

There was volcanism all along the Outer Himalaya in Early Permian – a chain of volcanoes formed possibly along deep faults due to rifting:

Shahbazagarha in northern Pakistan; Pir Panjal in Kashmir; Bhaderwah-Chamba in western Himachal; Dugadda-Rathwadhab belt in southern Garhwal; Tansen hill in south-central Nepal; Barahkshetra in southeastern Nepal; Ranjit valley in southern Sikkim and Bhutan, and Jirdo in Eastern Arunachal.

Permo-Carboniferous magmatism in the Indian subcontinent includes the alkalic province of Peshawar, comprising the 294 Ma Malakand granite and 297±4 Ma Ambela ijolite, several hundred metres of intermediate to silicio-welded tuffs above the glaciogenic deposit in the Agglomeratic Slate, and the 311±1 Ma Mandi leucogranite and the 284±1 Ma Yuman anorogenic granite in Ladakh. In the Eastern Himalaya the Abor Volcanics comprise basaltic and andesitic flows, silicic tuffs and agglomerates.

Table 6.5. Palaeozoic sequences in various sectors (Bhargava, 2008, p.212)

Period		Salt Range / Rajasthan	Kashmir	Zanskar-Spiti	Uttarakhand-Kinnaur	Nepal	Bhutan	Peshawar	Lesser Himalaya
Permian	L	Zaluch Group	Khunamuh	Gungri	Kuling Shale	Nenjung	Barishong		
	M		Panjal Volcanics	Panjal Volcanics					
	E	Nilawahan Group	Nishat Bagh & Mamal Beds Pindabol	Gechang Ganmachidam	Girth Fm.	Senja		?	Bijni
Carboniferous	L					Thini Chu	Ripakha		
	M		Fenestella Shale	Po				Zaffar Kando	
	E		Syringothyris Lst.	Lipak		Ice Lake		Khybar L	
Devonian	L		Wazura		Kali Fm.	Tilicho Pass		?	
	M		Wazura - Muth	Lipak - Muth				?	
	E		Muth	Muth	Muth				
Silurian	L							Nawshera	
	M		Gugaldhar	Takche	Shiala-Yong	Chandragiri, C	Wachi La	Kandar	
	E				Shiala-Yong	Chitlang Dark Band Lst.			
Ordovician	L				Shiala-Yong				
	M		Hallamulla	Thango	Ralam Fm.	Damgad		Panjpir	
	E							Misri Banda	
Cambrian	L		Hapatnar Group	Haimanta Group			Quartzite		
	M	Jhelum Group					Maneting		Tal Group
	E				Milam	?		Amber	

7

Gondwana Supergroup

INTRODUCTION

There was a profound hiatus spanning about 250 Ma, subsequent to the deposition of Vindhyan and Kurnool sediments (Neoproterozoic to Early Cambrian?) in Peninsular India. It was during the closing phase of uppermost Carboniferous that deposition of glacial sediments was initiated in a number of basins in some parts of Peninsular India, most of them confined to major river valleys, namely the Damodar, Son, Mahanadi and Godavari. Deposition in these basins continued up to Early/Middle Mesozoic and also in a few places along the coasts and southern sections of Himalaya. Though these sediments were essentially terrestrial, some evidence exists for marine intercalations. It was to this sequence of sediments that H.B. Medlicott coined the term 'Gondwana' after an aboriginal Gond tribe of Central India. The term was mainly used to denote the glacial boulder beds and succeeding conglomerates, sandstones, shales and coal measures of fluviatile and lacustrine origin from Peninsular India, ranging in age from Upper Carboniferous to Upper Jurassic/ Early Cretaceous. Subsequently, sediments, flora and fauna of the Gondwana affinity are recorded almost in all the southern continents of the world. However, it was Edward Suess (Austrian Geologist) who conceived of the great southern continent of Gondwana in 1885. He used the word Gondwanaland to the Indian Peninsula, Madagascar (now Malagasy), Central and Southern Africa, stressing their common features in their geological history. He later included Australia and South America. Subsequently further investigations led to Antarctica also to be included in this supercontinent.

The formations of Gondwana collectively comprise more than one system of the internationally recognised standard sequence, and the upper limit of the whole group of formations transgresses the boundaries of the now established International Geological Time Units (Chapter 2).

Lower age limit of Gondwana sequence, when critically evaluated in context of marine basins in High Himalaya is early Permian. The marine

incursions in Umaria and Manendragarh also aid in arriving at this age. The upper age limit of the Gondwana sequence may be Early Cretaceous based on the occurrence of Umia Plant Beds associated with Lower Cretaceous marine strata in Kutch.

Characteristics

The Gondwana basins of Peninsular India (Fig.7.1) contain mainly a thick pile (~200 m to as much as 4000 m) of clastic sediments preserved in graben/ half-graben bounded by high angle normal faults. The Gondwana basins are believed to represent remnants of an originally extensive and thicker master basin whose palaeoslope was towards northwest. It is found that the main depocentres of Gondwana sedimentation are confined to the existing major river valleys and are along and within the earlier Precambrian tectonic fabric.

The following are considered to be the essential requisites of Gondwana stratigraphic units:

(i) A glacial boulder bed to start with (in some of the basins), followed by sandstone, shale and coal in an ascending sequence in the lower part
(ii) preservation and/or deposition in intracratonic narrow linear faulted basins
(iii) largely fluvio-lacustrine depositional environment, except for the glacio-marine influence near the base in some cases
(iv) presence of *Glossopteris* and *Ptilophyllum* flora and
(v) an almost consistent west or northwest directed palaeoslope

All these characteristics may not necessarily apply to those sediments containing the above plant fossils in the peripheral regions along the coasts or in the foothills of Himalaya. Unlike the Permian and Triassic span of the largely non-marine Gondwana sequence in Peninsular India, the marine equivalents in the Extra-Peninsular India are largely Lower Permian and Lower Cretaceous in age; a major part of the Permian and the entire Triassic is mostly absent. The floral beds associated with these marine sequences are considered to have been transported by streams into the basins where they are now found.

It may, however, be mentioned here that there is a strong opinion among some of the earth scientists in India that the sequence of sediments in the peripheral regions need not be relegated to Gondwana, just because they contain plant fossils of those periods.

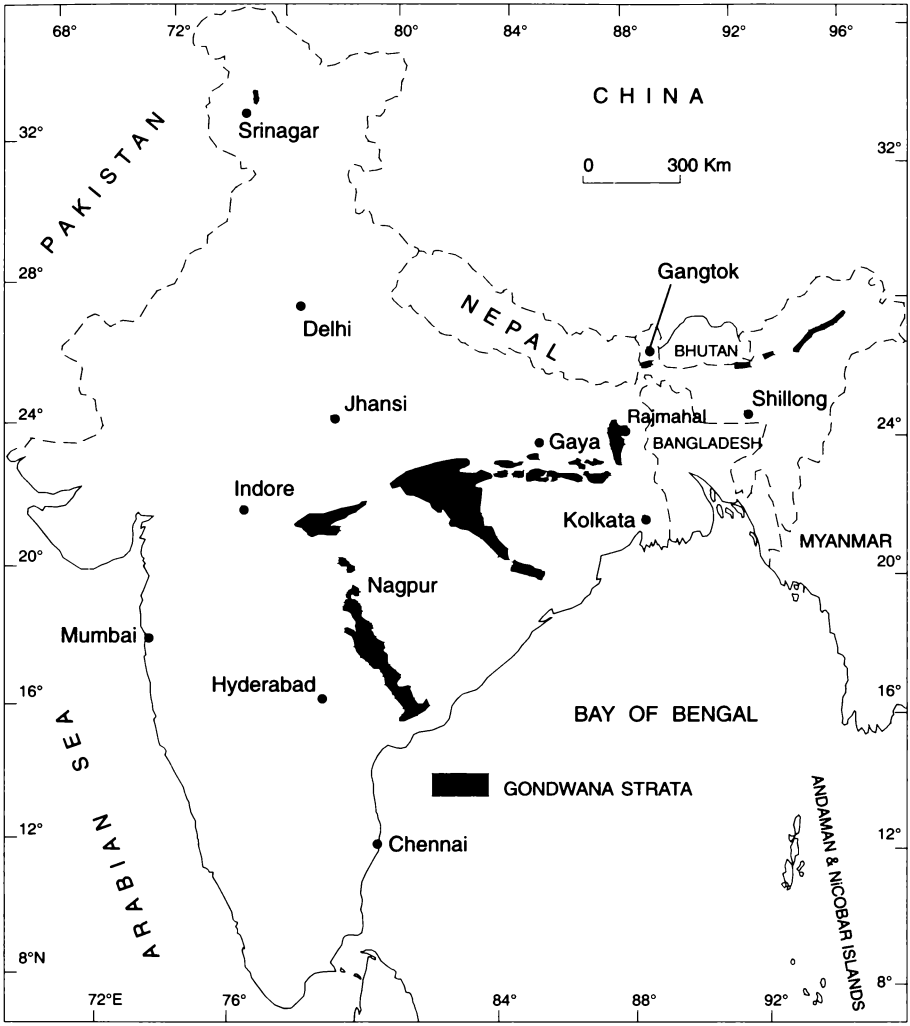


Fig.7.1. Major Gondwana strata in India.

STRATIGRAPHY AND STRUCTURE

A major part of the Gondwana sediments are confined to the three tracts, which include Koel-Damodar, Son-Mahanadi and Pranhita-Godavari basins. Even in these there are many sub-basins separated from each other by older Precambrian basement highs and ridges. Table 7.1 presents a generalised classification and correlation of various stratigraphic units in Indian Gondwana formations.

Two schemes of classification were proposed for the Gondwana on the basis of their lithological and palaeontological considerations: (i) Two-fold classification by W.T.Blanford, who divided the Gondwana sequence into lower

Table 7.1. Stratigraphic correlation of different peninsular Gondwana basins (Source: Pant and Murty, 2004, p.32)

Age \ Area	Rajmahal	Damodar	Son-Mahanadi	Rewa	Satpura	Godavari Valley	East Coast	Kutch
Lr. Cretaceous	Rajmahal Traps/ Sediments			Bansa & Chandila beds	Jabalpur F	Chikiala & Gangapur F.	Athgarh, Golapalli, Raghavapuram, Tirupati beds	Umia F
Jurassic: Upper								Marine Jurassic
Jurassic: Middle								
Jurassic: Lower						Kota F		
	Dubrajpur F	Supra-Panchet F/ Mahadeva F	Supra-Panchet F					
Triassic: Upper				Parsora F	Mahadeva F (?): Bagra F	Dharmaram M, Maleri M, Bhimaram M (Maleri F)		
	----------	Unconformity	----------					
Triassic: Middle					Denwa F	Yerapalli M (Maleri F)		
Triassic: Lower	Panchet F	Panchet F	Panchet F / Up. Kamthi F	Tiki F	Pachmahri F	Kamthi F: Up. Kamthi M, Mid. Kamthi M, Lr. Kamthi M		
Permian: Upper		Raniganj F	Raniganj F/ Lower Kamthi F (coal-bearing)	Pali F: Upper Pali M	Bijori F (Thin coal-bearing)			
Permian: Middle		Barren Measure F	Barren Measure F	Pali F: Middle Pali M	Motur F	Barren Measure F		
Permian: Lower	Barakar F Karharbari F	Barakar F Karharbari F	Barakar F Karharbari F	Pali F: Lower Pali M; Barakar F Karharbari F	Barakar F	Barakar F		
U Carboniferous/ Lr Permian	Talchir F.	Talchir F	Talchir F	Talchir F	Talchir F	Talchir F	Talchir F	
---------- Unconformity ----------								
PRECAMBRIAN								

Note: F = Formation; M = Member

and upper divisions and the line of separation being top surface of the Panchet Stage (Carnic to Noric). The lower and upper Gondwanas are characterised by the *Glossopteris* and *Ptilophyllum* floras respectively. (ii) Three fold classification by Hughes, who identified a mixed flora called *Dicroidium* in between the *Glossopteris* and *Ptilophyllum* floras. Vredenburg also proposed a three fold classification and his middle division included 'Kamthi Series,' 'Panchet Series' and 'Maleri Series.' Since over a century the Gondwana sediments have been divided into an Upper and Lower Groups (as supported by Blanford, Medlicott, Oldham, Fox, Pascoe and Krishnan) and is being followed in most of the publications.

Three major groups of faults are recognised in the Gondwana basins. They include what are generally termed "boundary faults," which are in fact basin margin faults, intra-basinal faults and basin marginal cross faults. A perusal of the detailed geological maps of the Jharia and Raniganj coalfields will clearly illustrate examples of all these three. The basin marginal faults, with variation in amounts of downthrow and presence on one side or both sides, have given rise to half-grabens, homoclinal dips and sometimes asymmetric synclinal basins. These faults range in time almost from early Talchir times to close of Gondwana sedimentation, namely Late Jurassic to Early Cretaceous and even considered to have lingered on to early Cenozoic.

Damodar Valley

The most important coalfields of the Damodar Valley include Raniganj, Jharia, Bokaro, North Karanpura, Ramgarh, South Karanpura, Hutar, Auranga, Daltonganj, Jaintia, Saharjuri and Giridhi basins (Fig.7.2).

A generalised stratigraphic succession of the Damodar Valley coal basins is as follows:

LOWER GONDWANA	Panchet Group	Supra-Panchet Fm.
		Panchet Fm.
	Damuda Group	Raniganj Fm.
		Barren Measures Fm.
		Barakar Fm.
		Karharbari Fm.
	Talchir Group	Talchir Fm.

The Damuda Group comprises the basal Karharbari Formation, followed by Barakar, Barren Measures and Raniganj Formations. The group derives its name from the Damodar river that flows from the Karanpura basin in the west through Bokaro, Jharia and Raniganj basins where it is well developed. These

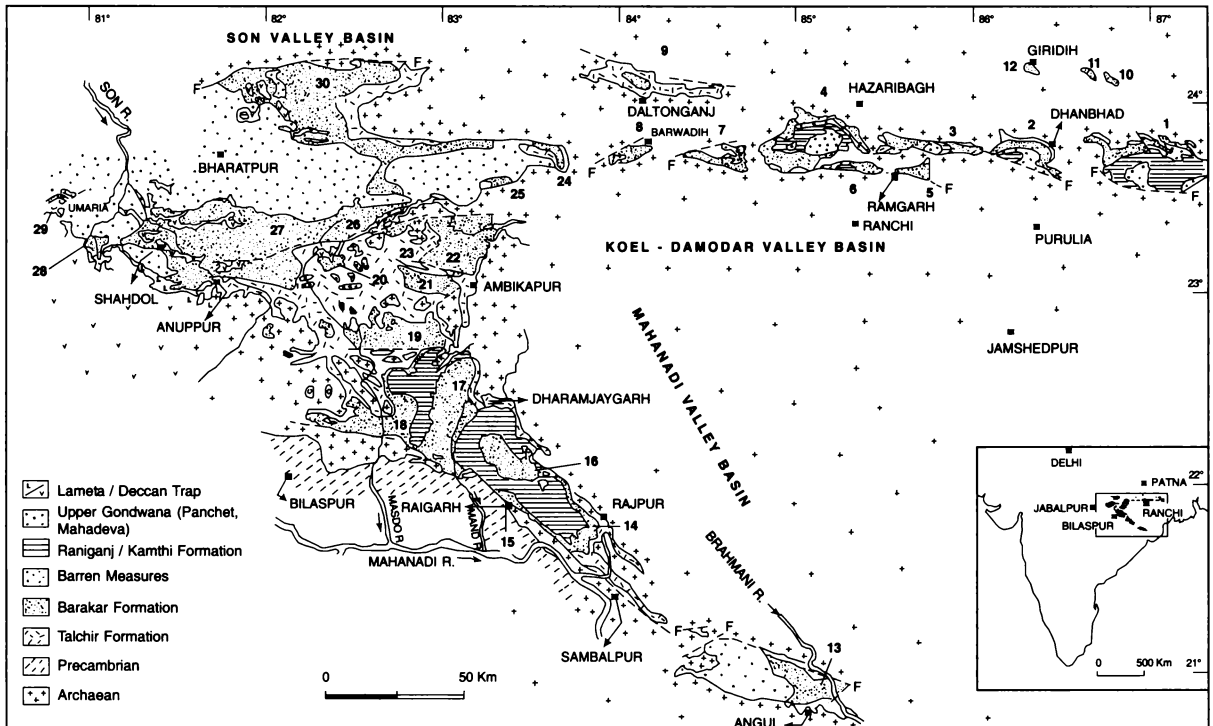


Fig.7.2. Geological map showing the distribution of Gondwana rocks in the Son-Mahanadi and Koel Damodar Valley basins. Inset shows the location of the Gondwana basins. Numbers (1)-(30) refer to coalfields. (**1**) Raniganj, (**2**) Jharia, (**3**) Bokaro, (**4**) North Karanpura, (**5**) Ramgarh, (**6**) South Karanpura, (**7**) Hutar, (**8**) Auranga, (**9**) Daltonganj, (**10**) Jainty, (**11**) Saharjuri, (**12**) Giridih, (**13**) Talchir, (**14**) Ib-river, (**15**) South Raigarh, (**16**) North Raigarh, (**17**) Mand River, (**18**) Korba, (**19**) Hasdo Arand, (**20**) Chirimiri, (**21**) Lakhanpur, (**22**) Bisrampur, (**23**) Jhillimili, (**24**) Ramkola, (**25**) Tatapani, (**26**) Sonhat, (**27**) Sohagpur, (**28**) Johilla, (**29**) Umaria, (**30**) Singrauli (after Casshyap and Tewari, 1984). (Reprinted with permission from Blackwell Publishers).

formations are generally characterised by fining upward sequences. They generally pass up gradationally without any conspicuous unconformity. It is over these that Panchet Group lies with a profound unconformity.

Talchir Formation: This overlies the Precambrian basement along an unconformable contact. Boulder bed/tillite, rhythmite, khaki green needle shale and light green sandstone constitute this formation. The boulder bed tillite is made of angular, poorly sorted pebble to boulder size clasts supported by sandy matrix. Clasts composition points to adjacent Precambrian provenance. The khaki green shale is silty, laminated, varved and breaks into needles. Dropstone clasts are common. Light green sandstone is micaceous, ripple and cross-stratified. Although the Talchir Formation is fairly represented in all the major coalfields of the Damodar Valley, it attains maximum thickness of 300 m in Daltonganj coalfield wherein besides *Glossopteris* flora marine fauna comprising *Eurydesma, Priondomya* and *Fenestella* are recorded. Sedimentary features indicate glacial and glaciomarine environment with palaeoslope towards WNW.

Karharbari Formation: Generally the 200 m thick Karharbari Formation succeeds the Talchir Formation along a gradational contact. However, at places sharp and overstep nature indicate local unconformity between the two formations. Conglomerates, pebble beds, coarse to very coarse-grained pebbly sandstone (gritty), siltstone, shale and thin streaks and bands of coal are met with. It contains coal seams in a few basins and the plant fossil *Gondwanidium burriada* biozone is considered as characteristic of this formation. Giridih coalfield is the type area for Karharbari Formation.

Barakar Formation: A 250 m thick Barakar Formation is the main repository of coal deposits. Sandstone, shale, carbonaceous shale and coal occurring in the form of fining upward cycles characterise this formation. An idealised cycle generally comprises the following sequence of beds:

(f) Coal, shaly coal
(e) Carbonaceous siltstone and shale
(d) Interbedded fine to medium sandstone, siltstone and shale
(c) Fine sandstone
(b) Coarse to medium sandstone
(a) Pebbly very coarse sandstone (bottom)

Truncation of beds (e) and (f) is common. Based on the development of beds (a) to (f) the cyclic units may be categorised into two types, viz. fully developed and truncated cyclothems. Thick coal seams are developed in the

cyclothems of lower and middle parts of this formation. Sandstone is feldspathic and displays tabular and trough cross-bedding whose palaeocurrent is towards west or northwest. Shale and coal seams abound in leaf and stem impressions of *Glossopteris* flora and related spore and pollens (palynofossils).

Barren Measures: As the name implies this formation is devoid of coal seams and is represented by alternating units of cross-bedded ferruginous sandstone, micaceous siltstone and ferruginous shale. The latter rock unit is also called Ironstone Shale in the Raniganj basin and Barren Measures in the remaining coalfields of Damodar Valley. These have gradational contact with both the underlying Barakar Formation and the overlying Raniganj Formation. Since some of them have iron content of 30 to 40%, they have been worked as iron ore in the beginning of the last century.

Raniganj Formation: In the type area, i.e. Raniganj coalfield, this formation attains a maximum thickness of 800 m. It consists of sandstones, shales and coal seams, the sandstones being fine-grained than those in the Barakar Formation. Workable coal seams are largely confined to this formation in Raniganj basin only.

Panchet Formation: The Panchet Formation is best developed in the Panchet Hill located along the southern fringe of the Raniganj basin and a few places elsewhere. Though not found in the Jharia basin, its presence is reported in Bokaro, North Karanpura, Auranga and Hutar basins. It is also found in the eastern part of Rajmahal Hills and in the Malda basin in West Bengal. It lies with an unconformity over the Damuda Group formations.

In the type area of the Raniganj basin, the formation comprises of greenish, buff and brown current-bedded sandstone (lithic to feldspathic arenite), shale and siltstone in the lower part. Maximum thickness of this formation is of the order of 500-600 m.

Supra-Panchet (Mahadeva): Maximum development of Supra-Panchet is found in the Bokaro basin, where it attains a thickness of 600 m in the Lugu Hill section. Coarse to very coarse sandstone interbedded with conglomerate, jaspery quartzite and also micaceous ferruginous silt and clay are prominent lithounits in this formation. Many of the prominent hills in some of the basins in Damodar Valley coal basins are capped by this formation. In most of these basins, the Supra-Panchet attains a thickness of about 200 m. It is inferred that this formation was perhaps present continuously across most of the basins but later erosion has left only a few remnants of these. Basal contact of this formation

is marked by angular unconformity. Ferruginous sandstone, conglomerate, pebble beds and red clay are prominent rock units of this formation.

Satpura Basin

The Satpura basin is located south of Narmada River and extends from Jabalpur to Lokartalai. Mohapani, Pench-Kanhan and Tawa Valley are prominent coalfields. The lower Gondwana sediments are exposed in a broad syncline whose southern limb is marked by Pench-Kanhan and Tawa coalfields and Mohapani is located on the northern limb. Most of the Lower Gondwana tracts are concealed by the Upper Gondwana sedimentary cappings. The Satpura basin (Fig.7.3) is spindle-shaped with a length to breadth ratio of 4:2. The entire area of the Satpura basin is about 1200 km^2. The shape of the basin is governed by the intersection of the three prominent tectonic trends (i) the ENE-WSW fault parallel to the Narmada-Son lineament in the north, (ii) the NW-SE trend conforming to the Dharwar tectonic grain in the west and (iii) the NE-SW trend parallel to the Eastern Ghat tectonic grain. Figure 7.4 represents a generalised stratigraphic column of the Satpura basin. The Matkuli Formation encompasses the Denwa and Bagra stages, which are believed to display intertonguing relationship.

About 490 m thick Talchir Formation is represented by diamictite, light green sandstone, olive green needle shale (varves) and rhythmites. Striated pavement, an unequivocal evidence for glaciation, is recorded from Popas nala

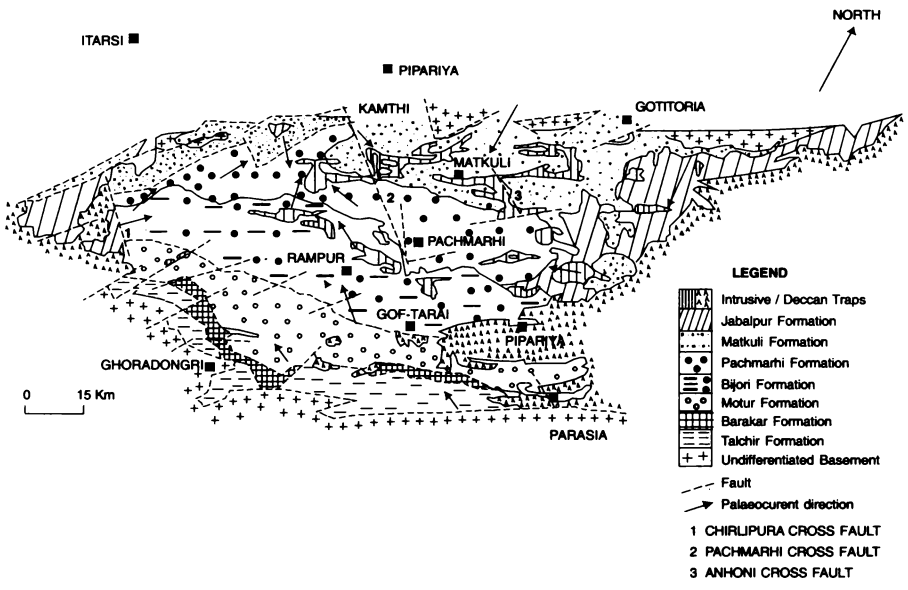


Fig.7.3. Geology and palaeocurrent map, Satpura basin (after James Peters and Singh, 2001).

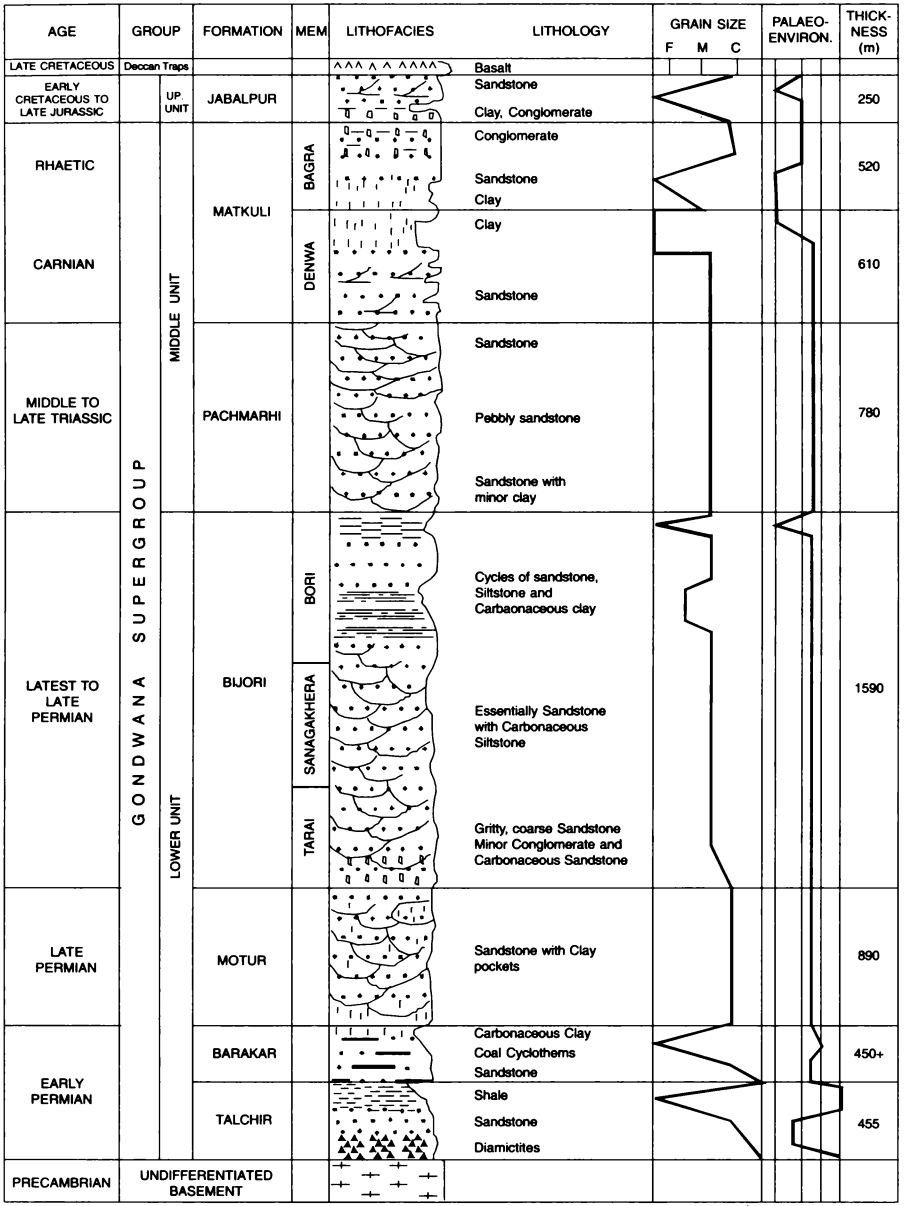


Fig.7.4. Stratigraphy of Satpura basin (after James Peters and Singh, 2001, p.317).

near Chordongri beneath a basal diamictite/tillite. Movement of glaciers was towards NW and WNW. Sandstone, carbonaceous shale and coal constitute the Barakar Formation, where upper part only is known to contain economically workable coal seams. Succeeding the Barakar Formation, along a gradational contact, is the Motur Formation (=Barren Measures) comprising red clay, feldspathic sandstone and grey shale with thin coal laminae. This formation

derives its name from Motur village located 18 km SSE of Pachmarhi. The Bijori Formation derives its name from the village of the same name and is said to be the equivalent of the Raniganj Formation. Maximum thickness of the Bijori Formation is estimated to be 1600 m. There is a variation in lithology, i.e. clays are prominent in the east whereas sandstones in the west. Besides *Glossopteris* flora, a labyrinthodont vertebrate *Gondwanosaurus bijoriensis* of late Permian age was recorded from this formation.

The type area of Pachmarhi Formation is in Mahadeo hill ranges, where it attains a maximum of 750 m thickness. Thick beds of white sandstones interlayered with pebble beds are the prominent rock units. The Pachmarhi Formation is devoid of any well preserved fossil remains. A 300 m thick Denwa beds (Formation) shows normal contact with the underlying Pachmarhi Formation. Sandstones and clays are prominent lithounits. The latter has yielded plant fossil *Phoenocopsis* along with labyrinthodonts *Mastodonosaurus indicus, Metaposaurus* and *Paratosaurus* of Early Triassic to Middle Triassic age. Recent surveys have indicated that the Bagra conglomerates overlie the Denwa clays. The 'Bagra beds' (Formation) is mainly a 180-240 m thick conglomerate sequence of late Triassic age.

Son-Mahanadi Valley

About 575 km long funnel-shaped Gondwana tract of Son-Mahanadi area includes E-W oriented Son Valley basin in the northwest and NW-SE trending Mahanadi Valley basin in the southeast. Most of the coalfields are located in Rewa-Chattishgarh areas. The coalfields of Son Valley part include Singrauli, Sohagpur, Jhillmili, Sonhat, Ramkola, Tatapani, Bisrampur etc. and those of the Mahanadi Valley are Korba, Hasdo-Arand and Mand-Raigarh. An E-W basement Precambrian high is a conspicuous feature in between Son and Mahanadi.

About 2200 m thick Gondwana lithic fill is classified into Talchir, Karaharbari, Barakar, Barren Measures, Raniganj/Kamthi (Lower Gondwana), Pali, Tikki and Parsora (Upper Gondwana) formations. The upper Gondwana is well represented in Rewa area.

The Talchir Formation in Son Valley area documents evidence for the distinct marine transgression at Manendragarh and Umaria. The Manendragarh marine shale bed is associated with basal tillite, whereas at Umaria the marine bed occurs above basal tillites and these are dated to be Asselian and Sakmarian ages respectively. The Barakar Formation is represented by coarse arkose, cross-bedded sandstone, shale, siltstone and coal seams and occur in fining upward cycles. The Barakar sediments are succeeded by a diverse lithological assemblage deposited over a long period in several sub-basins, in the Eastern

Son Valley, Rewa and Upper Mahanadi. The lithostratigraphic units and sedimentary characteristics of the Gondwana sediments are presented in Table 7.2.

Palaeocurrent analysis in the Son Valley part of the basin reveals northwesterly sediment transport throughout Mahadeva (equivalent to Panchet) sedimentation. The uniformity and consistency of northwesterly palaeoslope throughout the Gondwana sedimentation in the Son Valley evidently calls for extension of the given basin further north in the downslope direction beyond the north boundary fault (Son-Narmada lineament). The occurrences of outliers of Gondwana rocks, resting unconformably upon Bijawar and Vindhyan strata, north of the Son Valley, support such a possibility. The post-Gondwana, pre-Deccan Trap large-scale erosion in Central Peninsular India may have removed a substantial part of the sediments that might have been laid there.

Talchir Basin: The WNW-ESE oriented Talchir Basin is the easternmost Gondwana Basin of the Son-Mahanadi valley and bordered on all sides by the Precambrian basement with tapering end towards east. The Gondwana sediments preserved in this basin are classified into the Talchir, Karaharbari, Barakar and Supra-Panchet (Kamthi) Formations. The Talchir Formation is well exposed in SE, NW and northern part of the basin and shows converging dips. The Talchir Formation is named after the Talchir village in the eastern part of the coalfield. However, it may be noted that the present Talchir village is located on Karaharbari Formation. Thickness of this formation amounts up to 280 m. The Talchir Formation comprises of diamictite, needle shale and rhythmites. Sedimentological studies revealed that there were two periods of glacial advance and retreat during the deposition of Talchir sediments. The coal bearing Barakar Formation is well exposed in the eastern part whereas the western part of the basin is capped with the Kamthi Formation.

In the Ib river section the Talchir Formation is about 130 m, though in some places it is up to 280 m. The succeeding Karharbari Formation is around 270 m thick and contains a superior grade coal of seam I. Barakar Formation is the main coal bearing formation with a thickness of 500 m in Talchir and Ib river basins and has cyclothems of shales, carbonaceous shales and coal seams. These are unconformably overlain by Barren Measures (200 m non-coal) and Raniganj Formation (about 180 m in Ib river basin) and in turn overlain unconformably by Kamthi Formation in the Ib river basin.

Ichnostratigraphic ranges of 24 types of trace fossils have been established in the Talchir basin of Orissa. Ichnofacies tongues in conjunction with complementary marine invertebrate body fossils, unquestionably suggest strong infaunal activities and short-lived marine incursions, the most conspicuous of which are within the Talchir and Barakar Formations. Stromatolites are also

Table 7.2. General stratigraphic succession of Son-Mahanadi Graben (after Pande and Dave, 1998)

Age	Supergroup/ Group	Formation Rock unit	Lithology	Thickness
Paleocene to Upper Cretaceous	Deccan Trap	Deccan Trap Basalt/intrusives and extrusives	Fine grained basalts and dolerites	
~~

reported for the first time from the Talchir basin. These are of shallow marine cryptalgal origin.

Pranhita-Godavari Valley

The NW-SE trending Pranhita-Godavari Valley is unique as it preserves about 3000 m thick sediments deposited in a time span of 200 Ma from late Carboniferous/early Permian to Cretaceous. Most of the coalfields are located along the western margin at Sirpur, Bellampalli, Mandamari, Ramagundam, Chelpur, Pasra, Lingala, Kothagudem, Yellandu and Sattupalli, whereas Cherla and Manuguru are located in the east.

Generalised lithostratigraphic succession of the Gondwana sediments includes Talchir, Barakar, Barren Measures, Kamthi (Lower Gondwana Group), Maleri, Kota, Gangapur and Chikiala formations (Upper Gondwana Group) (Figs.7.5). The major structural elements are shown in Fig.7.5a.

The Talchir Formation unconformably overlies the Precambrian basement and attains a thickness up to 370 m. Diamictites, rhythmites and light green sandstone constitute the Talchir Formation. Glacial, glacio-lacustrine and glacio-fluvial depositional environments are favoured. The Barakar Formation is about 350 m thick and made of pebble beds and coarse feldspathic sandstone in the lower part and coal-bearing fining-upward cyclothems in the upper part. In addition to *Glossopteris* sp., *Gangamopteris, Schizoneura* sp. and *Vertebraria* sp., Grey Shale has yielded rich microfloral assemblage dominated by *Indotriradiites*, *Rhizamospora, Faunipollenites* and *Scheuringipollenites* of Early Permian affinity. A 60-800 m thick, middle to late Permian Barren Measures Formation overlies the Barakar Formation with a normal contact. Light yellow feldspathic sandstone, siltstone and grey shale are prominent lithounits. *Glossopteris* flora and microflora characterised by *Densipollenites* and *Crescentipollenites* are recorded.

The Kamthi Formation, named after Kamptee in Maharashtra, is known to have widespread distribution and covers over two-thirds of the basinal area. However, recent surveys have revealed that about 7000 km^2 area earlier marked as Kamthi Formation is now found to be an assortment of all the Gondwana stratigraphic units of the area. The Kamthi Formation shows 'overstep' nature over the older Talchir, Barakar and Barren Measures Formations. The thickness of the Kamthi Formation ranges from 50-400 m and contains conglomerate, conglomeratic sandstone, siltstone and shale of early Triassic age.

The Upper Gondwana Group begins with 250 m thick Maleri Formation comprising reddish brown to greenish grey clay, siltstone, argillaceous sandstone and lime-pellet rock along with middle to late Triassic fauna. The succeeding

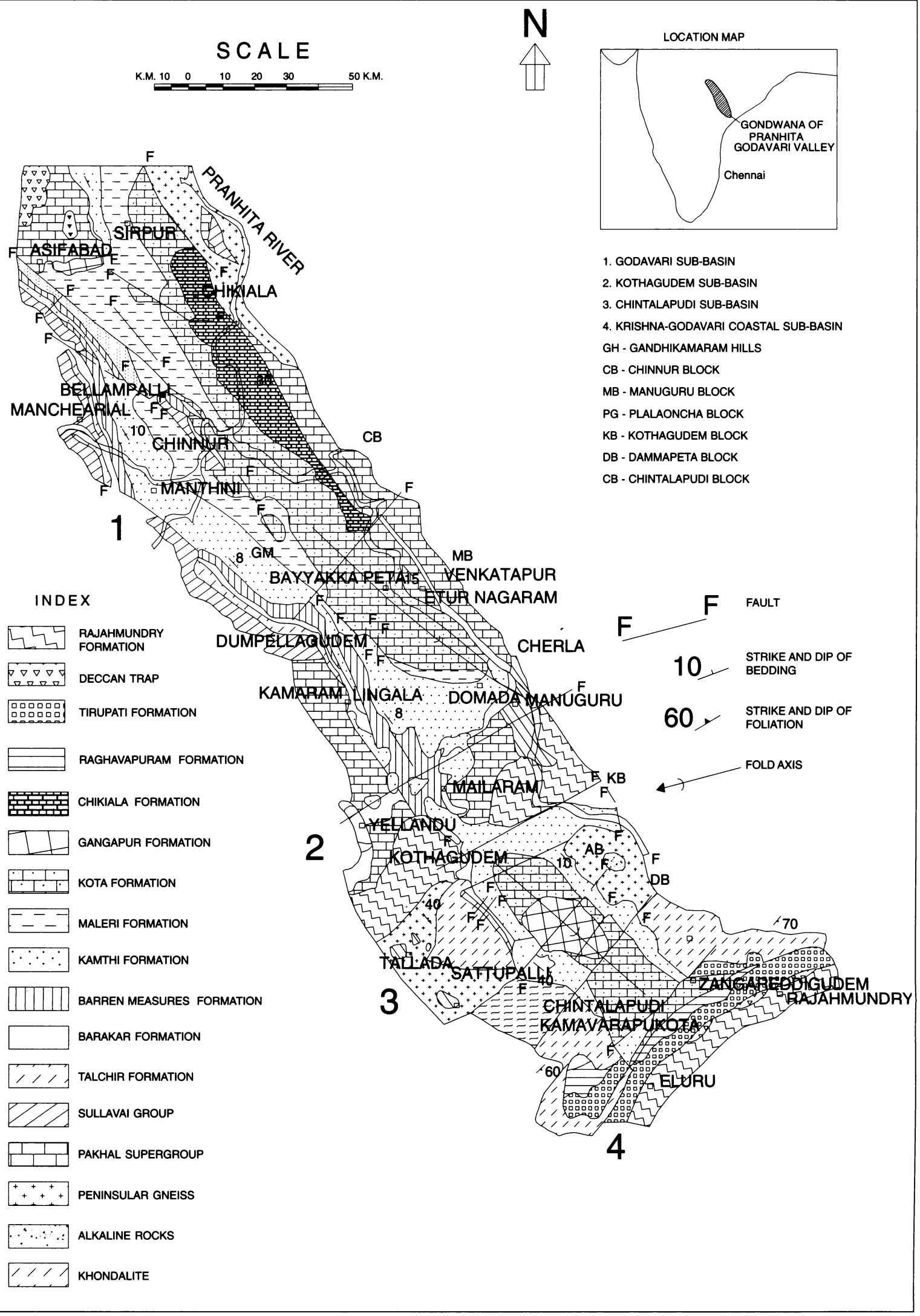


Fig.7.5. Geological map of the Pranhita-Godavari valley, Andhra Pradesh (Courtesy: G. Lakshminarayana).

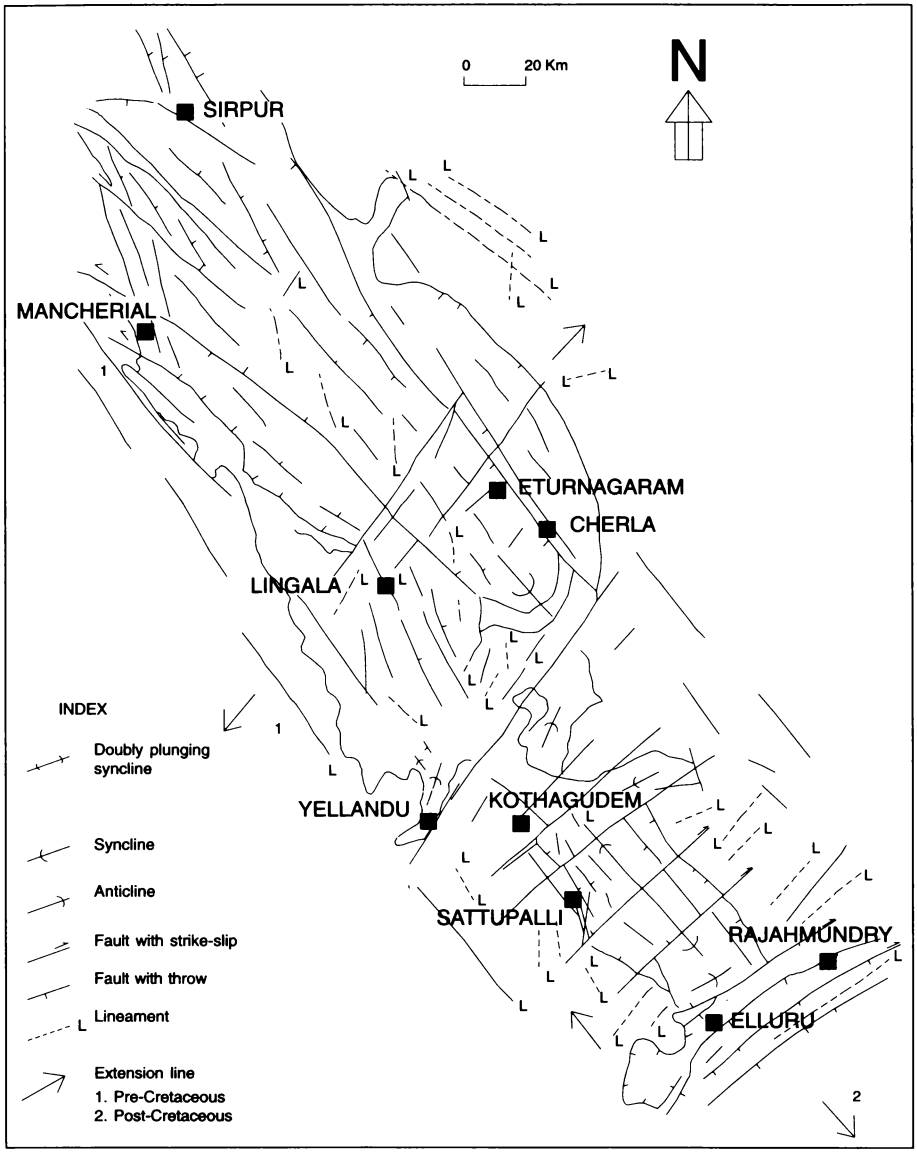


Fig.7.5a. Major structural elements in the Godavari rift (Courtesy: Lakshminarayana).

Jurassic Kota Formation includes large-scale cross-bedded sandstone along with *Ptilophyllum* flora in the lower part, fish and dinosaur-bearing limestone in the middle and upper sandstone and clay with *Ptilophyllum* flora. White sandstone, buff siltstone and light grey clay along with well-diversified *Ptilophyllum* flora of Neocomian-Aptian age characterise the Gangapur Formation. Lithoassemblage of the Chikiala Formation includes unfossiliferous conglomerate, conglomeratic sandstone and ferruginous sandstone of post-Aptian (?) age.

The Pranhita-Godavari Gondwana basin consists of a series of NNW-SSE grabens and half-grabens. Three prominent fault patterns are identified viz. (i) NNW-SSE trending syndepositional faults that controlled sedimentation and graben/half-graben development, (ii) NW-SE faults that imparted en echelon fabric to southwestern margin and (iii) the NE-SW transverse faults, oriented parallel to the grain of the Eastern Ghat Mobile Belt transecting the Godavari valley basin into different sub-blocks (Fig.7.5). It is considered that the progressive subsidence of these blocks in a southeasterly direction paved the way for the deposition of coastal Gondwana tract, a three-armed radial rift system in which the Godavari valley remained an aborted rift or aulacogen in Early Cretaceous, while drifting about the remaining two arms led to the development of the east coast of India. A 3000 m thick Gondwana lithic fill consisting of multifacies associations is preserved in this NW-SE oriented intracratonic basin set across the Eastern Ghat Complex (EGC). The depositional environments varied from glaciolacustrine to highly sinuous fluvial.

Phased uplift of the EGC during Mesozoic imparted changes to the Permian intercontinental drainage system, which started supplying increased amount of detritus to the basin. Basinal marginal faults were first formed at the beginning of the Triassic. The early Jurassic uplift of the Mailaram High (Fig.7.6) in the north imparted westerly shift to the braided rivers during the Kota sedimentation. Due to the prominence of Kamavarapukota ridge (Fig.7.6) in the south by early Cretaceous, the drainage pattern became centripetal, and short-lived high sinuous rivers debouched into the basin. The silting up of the Chintalapudi sub-basin with the sandstone-claystone sequence of the Gangapur Formation marks the culmination of the Gondwana sedimentation, perhaps coinciding with the break up of India from the Gondwanaland along the east coast. An interesting outcome of a detailed study of the Chintalapudi sub-basin and the Coastal Gondwana basin in the Krishna-Godavari tract is the recognition of the Godavari Triple Junction (Fig.7.7) and a sequence of events, which trace the transformation from continental Gondwana to coastal Gondwana.

Wardha Valley

The Gondwana rocks of the Godavari Valley extend northwestward into the Wardha Valley of Maharashtra. Important coalfields are located in an area of about 4150 km^2 that have geological succession similar to that of the Godavari Valley. As in the Godavari Valley, Archaean gneisses and Proterozoic Pakhal and Sullavai sequences constitute the basement.

The Gondwana sediments comprise the Talchir, Barakar, Kamthi and Maleri Formations. Striated pavement at Irai provides unequivocal evidence for glaciation during the Talchir deposition. A prominent unconformity separates

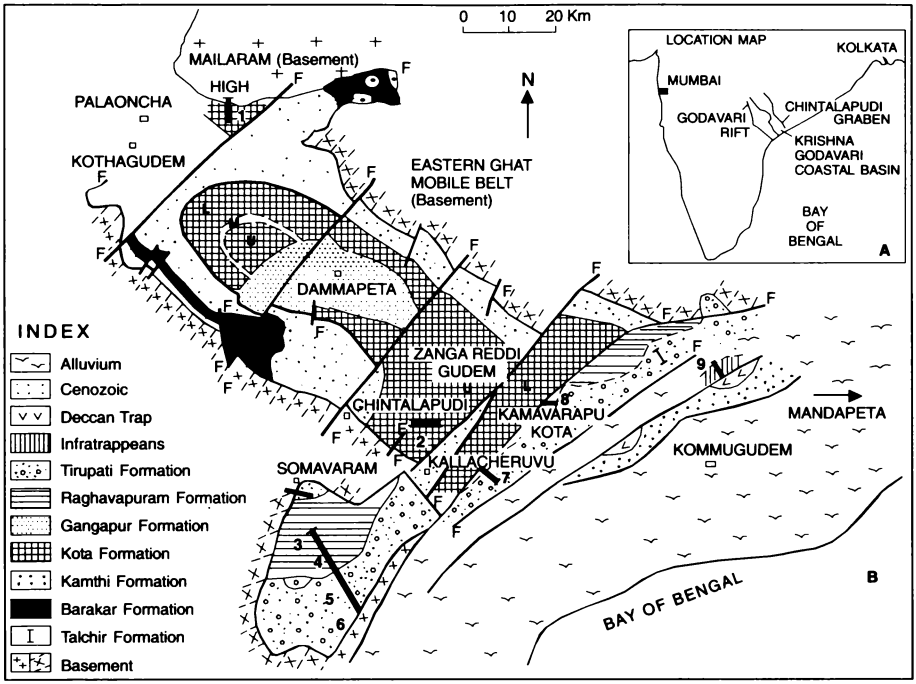


Fig.7.6. A. Location map of the Godavari Triple Junction. **B.** Geological map of the Godavari Triple Junction (after Lakshminarayana andMurti, 1990; Lakshminarayana et al. 1992). **CG** - Chintalpudi Graben, **KGCB** - Krishna Godavari Coastal Basin. **1** - Palaoncha hill, **2** - Jilakaraagudem, **3** - Nehrunagaram, **4** - Musunuru, **5** - Gollapalli-Dugut, **6** - Mirzapuram, **7** - Tadikalapudi, **8** - Raghavapuram, **9** - Duddukuru. L - Lower, M - Middle, U - Upper. (from Gondwana Research, v.5(1), p.228; © International Association of Gondwana Research)

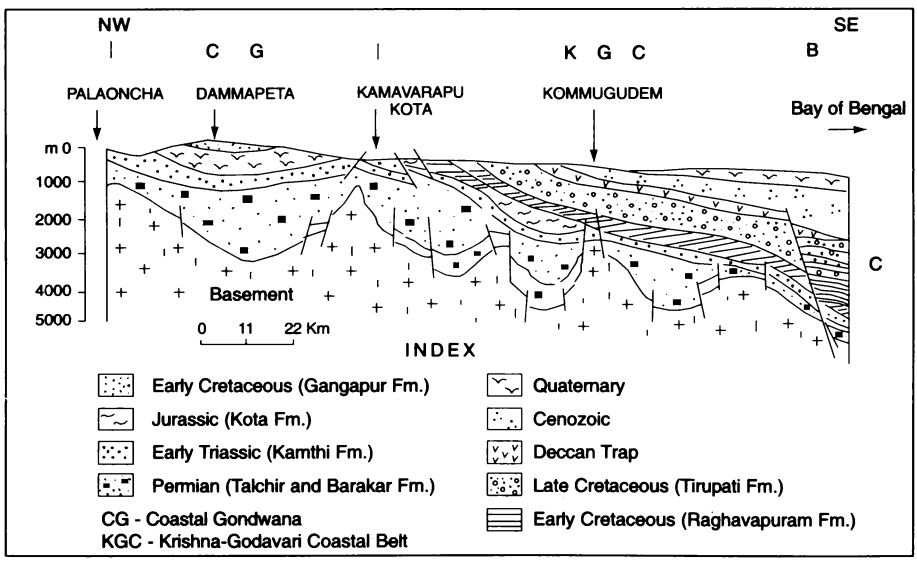


Fig.7.7. Schematic geological cross section across the the Godavari Triple Junction. (after Lakshminarayana 2002). (from Gondwana Research, v.5(1), p.229; © International Association of Gondwana Research)

the Barakar and Kamthi Formations. The latter have wide areal extent and overlap the older formations. The Wardha coalfield is a broad anticline plunging NNW. The Sasti, Ballarpur, Lalpeth, Mahakali and Rayatwari collieries are located along the eastern limb, whereas Ghugus, Majri, Telwasa and Chinchala areas constitute the western limb.

Kamptee, Bandar and Umarar coalfields: The Kamptee coalfield, located about 20 km NNE of Nagpur, comprises an ascending succession of Talchir, Barakar, Motur, Kamthi and Lameta Formations. Most of the 'Coal Measures' are covered by younger sediments and Deccan Trap. Kamptee coalfield is the type area for the Kamthi Formation. Isolated coal bearing outcrops spreading over a hundred square kilometers are located at Bandhar and Umarar. Large areas in the Wardha Valley in the south and Pench-Kanhan Tawa Valley in the north are covered by Deccan Trap. Tracing the subsurface continuation of Gondwanas beneath the Deccan Traps involves integrated geological and geophysical surveys.

Rajmahal Basin

The Rajmahal Hills, situated in the northeastern part of the Jharkhand State, preserve Gondwana Formations comprising Talchir, Barakar and Dubrajpur Formations (Figure 7.8). These are overlain by the Rajmahal Formation made up of a series of basaltic lava flows and associated inter-trappean beds (Table 7.3). The Durgapur Beds correlatable to the Dubrajpur Formation shows wide areal extent in Damuda basin in the western part of Burdwan district, West Bengal and consists of feldspathic sandstone with occasional red and green shales, carbonaceous sandstones, carbonaceous shales and lenses of dull coal. The Durgapur beds is correlatable with Supra-Panchet in the Raniganj coalfield. The fossil plant-beds (inter-trappeans) at Katangi Hill are essentially cycadophytes and pteridophytes belonging to *Onychiopsis* sp., *Ctensis* sp., *Taeniopteris* sp. and *Pagiophyllum* sp. along with Upper Jurassic marker *Culcites* sp.

LIFE IN GONDWANA

Flora

Brongniart, in the early 1880s, described and illustrated *Glossopteris browniana* var.*indica* and *Glossopteris angustifolia* from the Raniganj coalfield. Ottokar Feistmantel not only undertook an exhaustive and intensive morphographic study of the Gondwana plants but also used the information for age determination and palaeobotanical zonation. In addition to profuse leaf

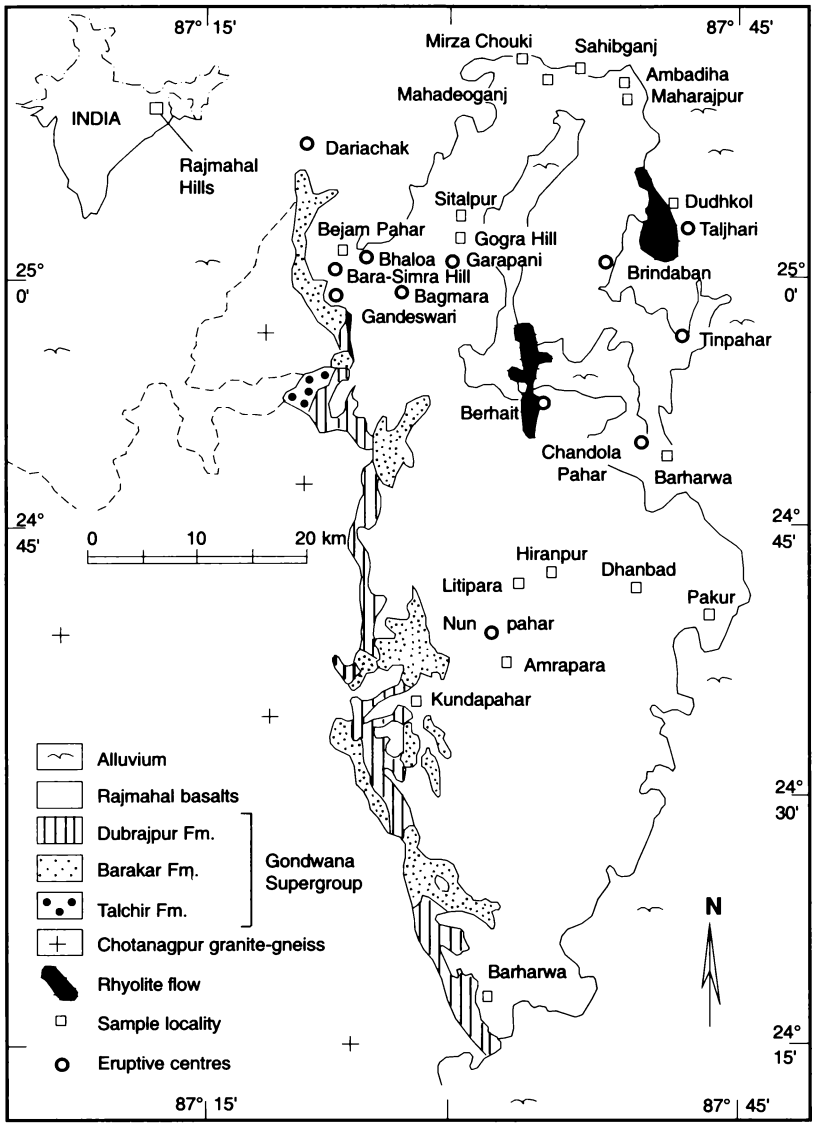


Fig.7.8. Distribution of basalt and Gondwana sediments as exposed in the Rajmahal Hills, Jharkhand State. The location of inferred volcanic vents are also shown. (after Ghose and Kent, 2003)

and stem impressions of *Glossopteris* flora, the upper stratigraphic levels of Raniganj Formation is characterized by the presence of fossil wood-*Dadoxylon,* whose trunks measure up to 30 m in length and diameter ranging from 35.5 to 75.5cm. Growth rings are well preserved.

In view of the fact that a majority of the plant fossils are common to most of the formations of Lower Gondwana, their stratigraphic range is presented in Table 7.4. (also see Plates 7.1 and 7.2).

Table 7.3. Lithostratigraphy of the Rajmahal Formations (simplified from Sengupta, 1988) (Source: Mahadevan, 2002, p.425)

	Alluvium	
	Laterite	
	D. Upper trap flows with and without intertrappeans scarcely fossiliferous	Cretaceous
	C. Upper trap flows with fossiliferous intertrappean Bed 8 with *Taeniopteris spatulata - Brachyphyllum rhombicum*. Assemblage zone 3	Lower Cretaceous
Rajmahal Formation	B. Lower trap flows (4 to 6) with fossiliferous intertrappean beds (4 to 7) with *Cladophlebis indica - Dictyozamites indicus*. Assemblage zone 2	Middle Jurassic
	A. Lower trap flows (1 to 3) with unfossiliferous intertrappean beds (1 and 2)	
	---------- Igneous contact ----------	
	Baked sandstone, siltstone	Lower Jurassic
Dubrajpur Formation	Fossiliferous siltstone with *Ptilophyllum acutifolium* and *Gleichenites gleichenoides*. Assemblage zone 1	
	Pebbly sandstone	
	Coarse sandstone, shale and clay beds	Triassic

Luxuriant vegetation was prevalent during Lower Carboniferous in Europe. It was then extremely cold in the Gondwana continent and many of the earlier plants must have died out, leaving a few stragglers like *Glossopteris* and some spores. *Glossopteris* flora was comparatively less luxuriant and less varied than the Northern flora – *Angara/Kuznetz* (Siberia) and *Cathaysian* or *Gigantopteris* (China, Korea, Sumatra and western part of North America). The main difference between the Palaeozoic and Mesozoic flora is that the former consisted mostly of extinct types of plants and the latter, in the Upper Trias, had some forerunners of the modern plants.

The arid conditions, which began in other parts of the world, were felt in India also during the Triassic period. The *Glossopteris, Gangamopteris, Schizoneura*, which are characteristic of the Permian age, slowly disappeared from India. *Equisetites* sp., *Sphenopteris* sp. *Cladophlebis* sp. and mega spores *Triletes* and *Pityosporites* began appearing in Triassic. *Dicroidium* is widely distributed in the Triassic of Gondwana. The sparsely developed Triassic flora gave place to well developed *Ptilophyllum* flora, seen in Rajmahal Hills and Jabalpur areas, Damodar Valley, Son-Mahanadi Valley, in Kota in Godavari Valley and the East Coast. Cycadophytes and coniferales became prominent at the expense of pteridosperms and filicales. A few gymnosperms also made

Table 7.4. Stratigraphic range of Mega Plant fossils in Lower Gondwana

Names of the plant fossils	1	2	3	4	5	6
Pteridospermae						
Glossopteris indica	x	x	x	x	x	x
Gangamopteris cyclopteroides	x	x	x	x	-	-
Gangamopteris angustifolia	x	x	-	-	x	-
Equisetale						
Schizoneura gondwanensis	-	x	x	-	x	x
Phyllotheca indica	-	-	-	-	x	-
Cordaitales						
Noeggerrathiopsis hislopi	x	x	x	x	x	-
Coniferales						
Buriadia sewardii	-	x	-	-	x	-
Cycadophyta						
Taeniopteris danaeoides	-	-	x	-	x	-
Sphenophyllales						
Sphenophyllum speciosum	-	-	x	-	x	-

1 - Talchir, 2 - Karharbari, 3 - Barakar, 4 - Barren Measures, 5 - Raniganj, 6 - Panchet.
x - reported occurrences.

their appearance. In the early part of the Cretaceous, there were some ferns and cycadophytes of the preceding period. The occurrence of a few plant species of the Gondwana terrain in parts of Central Asia and China, and similarly those of Angaraland in Kashmir suggest existence of some land bridges to permit this migration, in spite of being largely separated by the Tethys.

Palynomorphs

Palynomorphs are considered as one of the effective tools to identify the environmental changes that occurred at the time the vegetation flourished in the Gondwana continents and also best-suited tool for biostratigraphic zonation. It is more so for Gondwana sequence of India because of its dominantly non-marine depositional environment. They are complete units in themselves, the genetic characters are fully manifested through the phenomenon of evolution because the spores and pollen are the entities directly linked with the reproduction system; they are produced in astronomical numbers and theoretically must be found in most of the sedimentaries. The preservation potential is the highest in spores and pollen in comparison to other fossils because of the wonder material sporopollenin, of which they are made up. The range zone of selected taxa are more reliable element of palynoevent datum than the acme zones because the latter is based on numerical dominance of taxa which in the context of spatially separated regions could be biased by

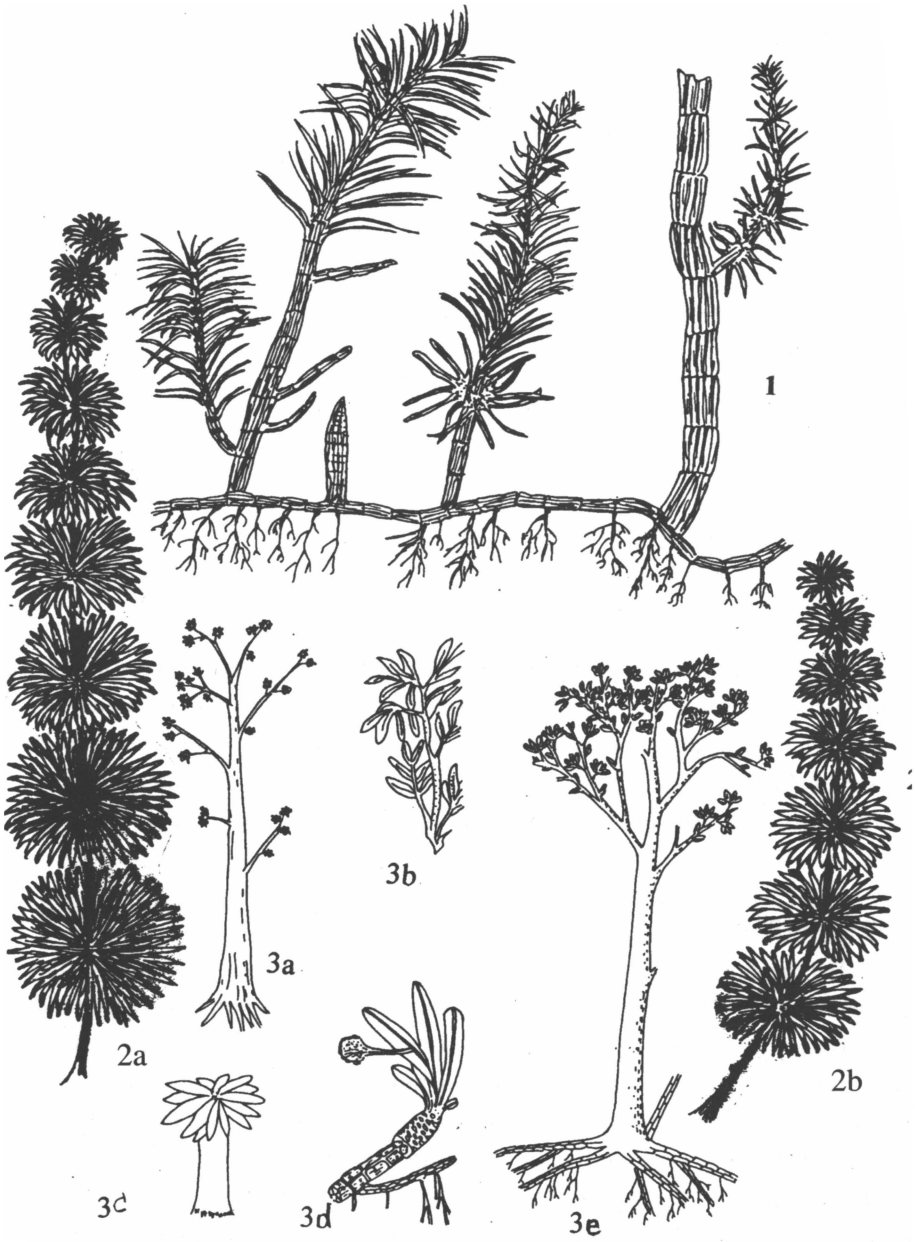


Plate 7.1. 1 - Reconstruction of the plant *Phyllotheca indica* (Lower Gondwana). **2a-b.** Reconstruction of the plant *Raniganjia bengalensis* (Lower Gondwana). **3a-e.** Reconstruction of the plant *Glossopteris* (Lower Gondwana). (Courtesy: B.S. Venkatachala and N.C. Mehrotra). (reproduced with permission from the Editor of the Palaeobotanist).

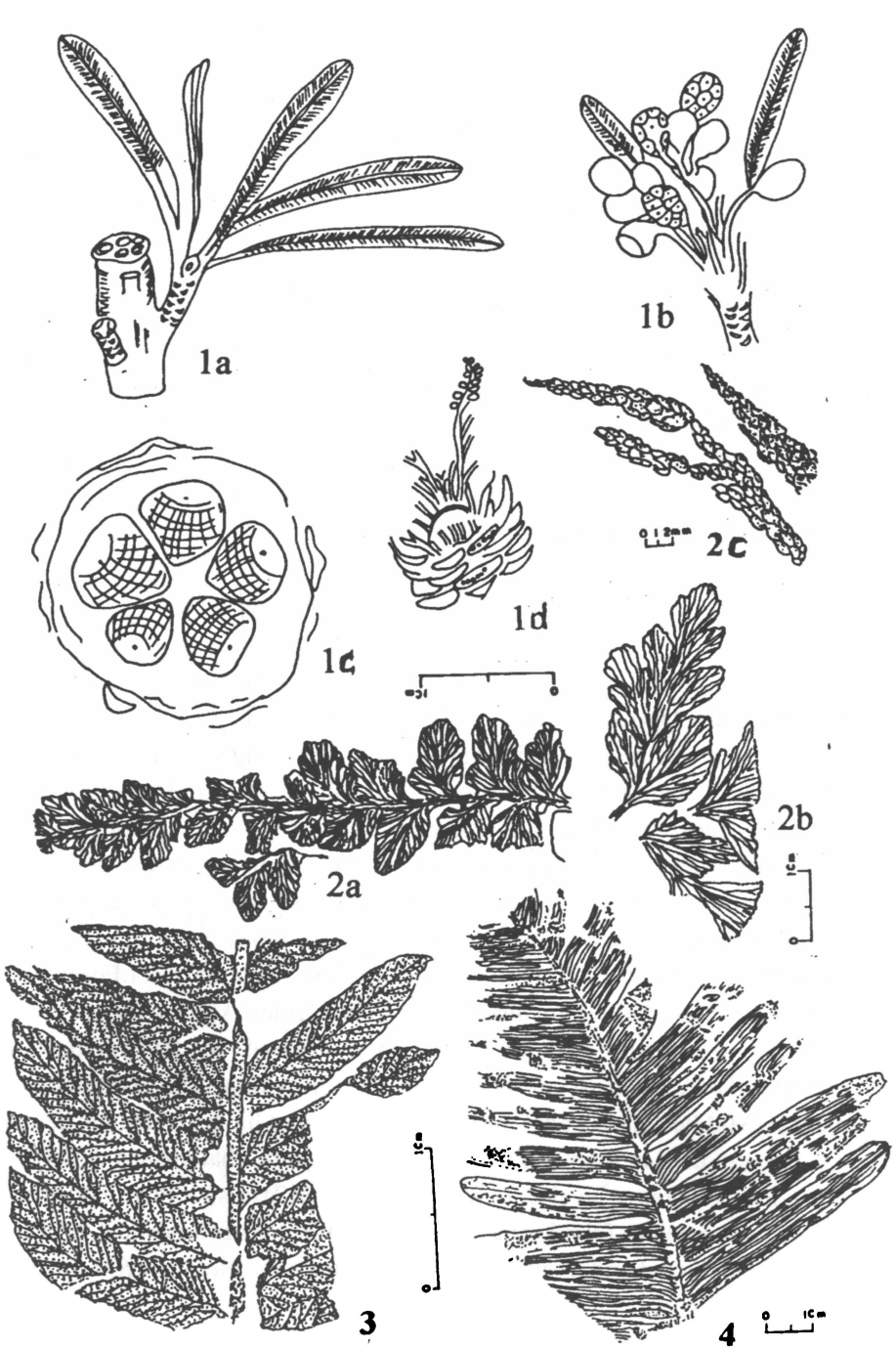


Plate 7.2. 1a-d - Reconstruction of *Pentoxylon sahnii* (Upper Gondwana). **2a.** *Thinnfeldia khatangiensis* (Upper Gondwana). **2b.** *Sphenopteris hislopi* (Upper Gondwana). **2c.** *Brachyphyllum mantillare* (Upper Gondwana). **3.** *Cladophlebis indica* (Upper Gondwana) **4.** *Pterophyllum morrisianum* (Upper Gondwana). (Courtesy: B.S. Venkatachala and N.C. Mehrotra). (reproduced with permission from the Editor of the Palaeobotanist).

ecological variabilities. Quite often FAD – First appearance datum and LAD-Last appearance datum of the species are indicated, which are most useful in correlation and classification. In Plate 7.3 is presented some of the important spore-pollen in Lower and Upper Gondwana.

The classification of the Gondwana sediments into Lower and Upper Gondwana Groups or Lower, Middle and Upper Gondwana Groups are mainly based on lithostratigraphic considerations with supporting floral or faunal associations. Formations included in each group display gradational contacts or local unconformities and also faunal/floral transitions. In order to further refine the Gondwana classification, some authors believe that the bio-stratigraphic classification based on palynofossils is appropriate and will better explain the variations in paleoclimates. Nevertheless, classification of the Gondwana sediments remains debatable and forms a fertile topic for research. Fig.7.9 presents the morphographic features of spores and pollen preserved in the Lower Gondwana formations.

Fauna

Vertebrate fossils are of considerable variety in the Gondwana Formations, particularly in the Upper Gondwana. Many of these show their relationship to those in other southern continents, which were part of the erstwhile Gondwanaland. A majority of vertebrate fossils were found in the Upper Gondwana sediments of Pranhita-Godavari Valley (Table 7.5), though some species have been described from some of the other basins as well. The interesting finds include crustaceans, insects, ostracodes and coprolites (fossilised excrements of vertebrates such as fishes, reptiles and mammals).

Kotatherium haldenii, a therian symmetrodont from the Kota Formation is the first reported earliest mammal from India. Oldest known Indian turtle *Indochelys spatulata* and the first ever record of flying reptile *Campylognathoides indicus* are both from this formation. The sediments of Carnic age (Middle Triassic age) in the Kota Formation have yielded the dental fossils of a non-therian mammal, *Gondwanodon tapani*, that pushes down the known oldest occurrence level from Rhaetic (terminal Triassic). Plate 7.4 shows some vertebrate remains found in the Mesozoic sediments of Gondwana, besides that of a reconstructed and mounted sauropod dinosaur skeleton of *Kotosaurus yamanapalliensis.*

Fossil reptile *Lytrosaurus* (one of the dicynodonts, a widely distributed group of the rapsids or mammal like reptiles) occurs in the Panchet Formation of Raniganj coalfield. They are also found in the Katberg Formation in the Karoo sequence in southern Africa and in the Fremouw Formation of Antarctica – all dated Triassic.

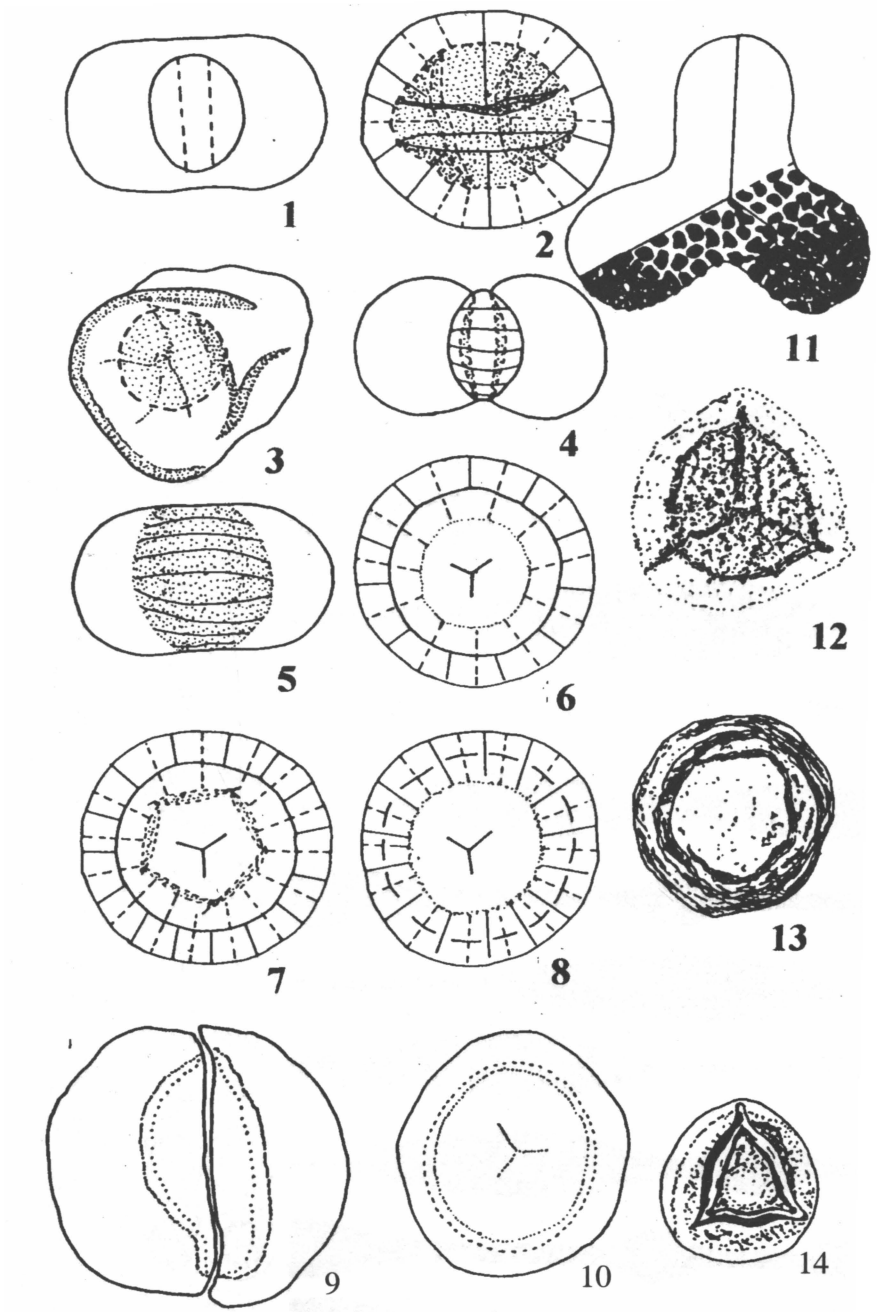


Plate 7.3. Lower Gondwana plant microfossils (spores and pollens). **1**-*Vesicaspora*, **2**-*Corisaccites*, **3**-*Densipollenites*, **4**-*Lunatisporites*, **5**-*Faunipollenites*, **6**-*Virkkipollenites*, **7**-*Plicatipollenites*, **8**-*Parasaccites*, **9**-*Alisporites damudicus*, **10**-*Virkkipollenites triangularis*. **11-14**. Upper Gondwana plant microfossils (spores and pollens). **11**-*Impardecispora apiverrucata*, **12**-*Aequitriradites spinulosus*, **13**-*Coptospora cauveriana*, **14**-*Classopollis meditriangulus*. (Courtesy: B.S. Venkatachala and N.C. Mehrotra). (reproduced with permission from the Editors of the Palaeobotanist and Geophytology).

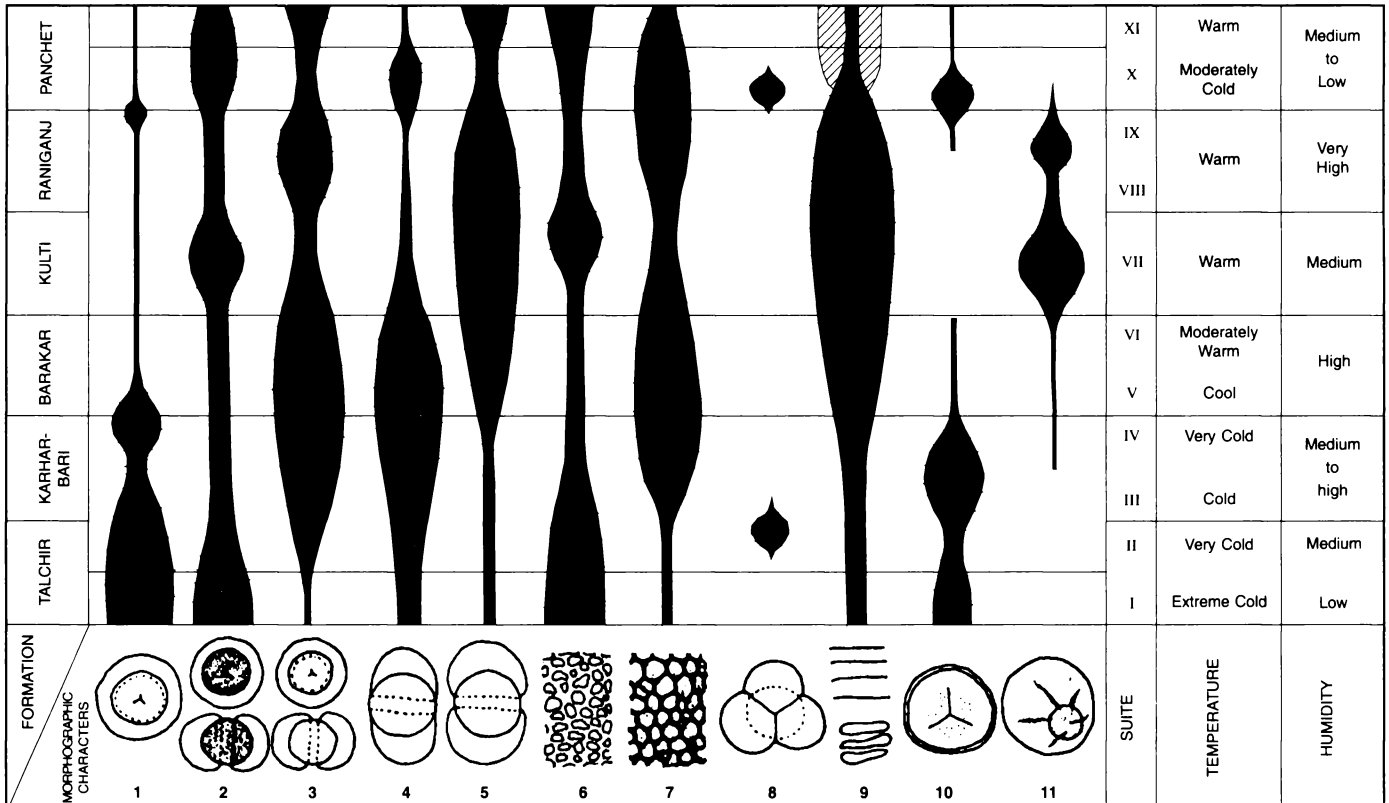
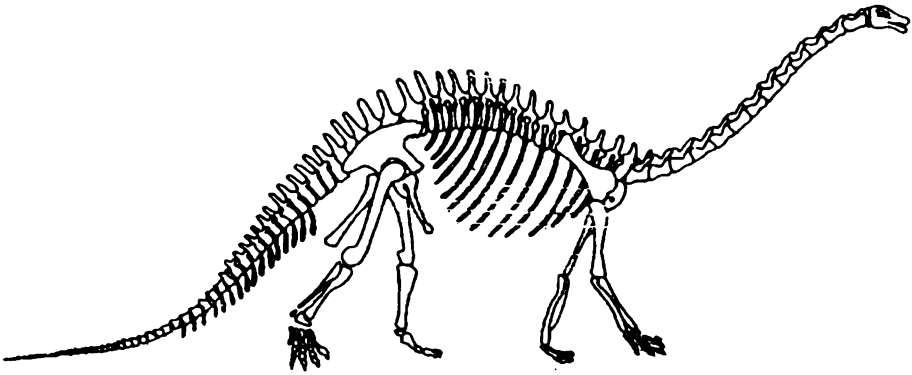


Fig.7.9. Trends in the distribution of morphographic characters, considered to be important from Talchir to Lower Panchet, in terms of relative abundance. **1.** Radial monosaccate; **2.** Dense central body; **3.** Thin central body; **4.** Haploxylonoid construction; **5.** Diploxylonoid construction; **6.** Leathery saccus; **7.** Non-leathery saccus; **8.**Tetrad of spores; **9.** Solid black striations and oblique lines: Taeniae; **10.** *Callumispora* and **11.** *Densipollenites.*(Source: Mahadevan, 2002, p.394)(with permission from Editor, Palaeobotanist, Lucknow)

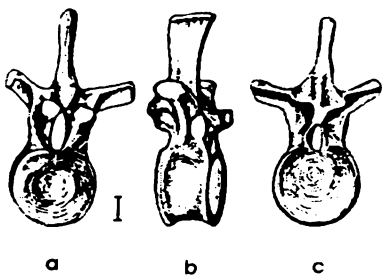
Table 7.5. Lithostratigraphy and fossils in P-G Valley (source: Bandyopadhyay et al. 1996)

Formation	Main Lithologies	Important Fossils	Age
Chikiala	Highly ferruginous sandstones and conglomerates		?
Gangapur	Coarse gritty sandstones, grey-white to pinkish mudstones with interbedded ferruginous sandstones and concretions	*Gleichenia, Pagiophyllum Ptilophyllum, Elatocladus*	Early Cretaceous
Kota	Sandstones, siltstones and mudstones with limestone bands	Holostean fishes, Sauropods Crocodylomorphs, Crytodire, Symmetrodons	Early to Middle Jurassic
Dharmaram	Coarse sandstones and mudstones	Prosauropods (large and small), Sphenosuchid	late Late Triassic
Maleri	Mudstones, fine to medium sandstones and calcirudites	Metaposaurids Chigutisaurids, *Parasuchia*, Rhynchosaurids, Aetosaurid	early Late Triassic
Bhimaram	Coarse to fine sandstones, ferruginous or calcareous at places and mudstones	–	late Middle Triassic
Yerrapalli	Mainly red and violet mudstones and calcirudites	Capitosaurs, Prolacerid Prestosuchid, Dicynodonts, Cynodont	early Middle Triassic
Kamthi	Sandstones and siltstones	*Glossopteris* flora	Permo-Triassic

Amphibian *Paratosuchus*, along with the reptiles *Wadiasaurus* and *Rechnisaurus* in the Yerrapalli Formation of the P-G Valley are comparable to the fauna *Dinodontosaurus* from South America and *Sangusaurus* from Ntawere Formation of Zambia of Middle Triassic age. The Maleri fauna of *Metaposaurus* in India, except for specific differences, is identical with *Metaposaurus* in Europe, North America and North Africa. The Kota Formation is known for the occurrence of well preserved sauropod dinosaur *Barapasaurus tagorei*. These occur well below a horizon containing undoubted Liassic (Lower Jurassic) fishes. Similar fauna is known from Africa and elsewhere in the Gondwana supercontinent. The reptiles collected from Pisdura and Jabalpur (Lameta Formation) are considered to belong to uppermost Cretaceous-Maastrichtian. A few of these occur in the Turonian or Santonian of Madagascar. A highly specialised and distinctive group of extinct mammals, the Sudamericidae (Gondwanatheria), is reported from the Late Cretaceous of Madagascar and India. This comprises the first evidence of Gondwanatheria



Kotasaurus Yamanapalliensis, a sauropod dinosaur skeleton reconstructed and mounted by the Geological Survey of India at Birla Museum, Birla Science Centre, Hyderabad.



Dorsal vertebra in (a) anterior (b) anterior-lateral (c) posterior views. The bar is 5 cm

A molar tooth of a micromammal from lower Jurassic Kota Formation

Teeth of dinosaurs, lower Jurassic Kota Formation

A complete humerus (fore limb element) of Sauropod dinosaur

Plate 7.4. Mesozoic vertebrates (Courtesy: P. Yadagiri).

outside South America and the first indication of cosmopolitanism among Late Cretaceous Gondwana mammals. Antarctica may have served as an important Cretaceous biogeographic link between South America and Indo-Madagascar.

The distribution of vertebrate fauna in different Indian Gondwana beds raises the question as to what extent they are results of migration or transportation. If the latter, their distribution may be explained either by India remaining a part of Gondwanaland until a late date in Cretaceous or through land connections between India, Madagascar and South America, well into late Cretaceous.

Trace Fossils

Ichnological findings from the Indian Gondwana basins provide a new insight into the role played by the ancient sea in shaping Upper Palaeozoic-Mesozoic Gondwana history. The ichnocoenoses with high density and diversity of *Skolithos* and *Cruziana* indicate shallow marine conditions. These zones occur as interstratified units within the continental Gondwana deposits at various stratigraphic levels and also within coal bearing Lower Gondwana succession. These ichnofacies tongues in conjunction with complementary marine invertebrate fossils, unquestionably suggest strong infaunal activities and short-lived shallow marine incursions. They also split the coal seams into transgressive-regressive couplets, a very common feature of shallow marine lower deltaic (paralic) coal deposits. Study of these trace fossils has aided very much in both correlation and inferring depositional environments in the Gondwana times in India.

Invertebrates

The marine intercalations particularly associated with the Talchir Formation in some basins contained invertebrates. For example, *Fenestella* sp. aff. *jabbiensis* (bryozoa), *Dielasma, Eurydesma hovbartene, E. playfordi, E. globosum* (brachiopods) are reported from Upper Talchir of Daltonganj basin (one of the sub-basins in Damodar basin). The marine fossils within Talchir Formation in Manendragarh and Umaria (Chapter 6) establish marine connections in Gondwana times.

COASTAL GONDWANA BASINS

East Coast

Regional synthesis of both surface and subsurface lithological, palaeontological, geophysical and tectonic data available for the sedimentary

basins of the east coast indicates a cogent geological and sedimentational history for the rocks of Cretaceous and Tertiary age in this belt. The megafloral assemblages of the east coast Upper Gondwana units are rich in pteridophytes and gymnosperms. *Ptilophyllum* sp., *Cladophlebis* sp. and *Elatocladus* sp. are ubiquitous. Invertebrate fossils viz. pelecypods, gastropods, ammonoids and foraminifera are associated with floral remains.

The coastal Gondwana formations occur as isolated outcrops along the east coast of India between Mahanadi in the north to Cauvery in the south. Prominent outcrops are located at Athgarh (Orissa), Ranasthalam, Eluru, Guntur, Ongole, Satyavedu (Andhra Pradesh), Sriperumbadur and Uttatur (Tamil Nadu). A conspicuous feature of the rocks is that *Ptilophyllum* flora is associated with marine invertebrates, thereby justifying the term 'Coastal Gondwana.'

Athgarh (Orissa)

Covered partly by laterite and partly by alluvium, about 400 m thick conglomerates, grits, carbonaceous shale, variegated shale and fireclay constitute the Athgarh Beds of Upper Gondwana at the head of the Mahanadi delta, near Cuttack. Palaeocurent in sandstone is towards southeast.

This formation has yielded the following early Cretaceous plant fossils: *Ptilophyllum, Marattiopsis macrocarpa, Cladophlebis indica, Rhiaomopteris ball, Thinnfeldia* and *Otozamites.*

Krishna-Godavari Coastal tract (Andhra Pradesh)

The NW-SE Continental Gondwana rift basin of the Godavari Valley is transversely superimposed by NE-SW trending Krishna-Godavari coastal tract. The contact between these two sedimentary basins defines a triple junction framework termed as the Godavari triple junction. The coastal Gondwana sediments in these areas unconformably overlie either Precambrian gneisses or the Kamthi and Kota Formations of the Godavari Valley. Table 7.6 shows revised stratigraphic succession of the Krishna-Godavari coastal tract.

Raghavapuram Formation: This comprises two distinct lithologies: (i) grey clay, siltstone and fine-grained sandstone with ptilophyllum flora which thrived in inter-distributary swamps of southeast flowing delta plain distributaries and (ii) white clay and sandstone characterised by a mix of ptilophyllum flora and invertebrate fossils (pelecypods, gastropods, ammonoids and foraminifera) of prodelta and shallow marine environment. This formation contains Early Cretaceous (Neocomian-Aptian age) palynofossil assemblage, represented by *Microcachryidites antarcticus*, *Contignisporites* sp.,

Table 7.6. Stratigraphic succession of the Upper Gondwana sediments in the Krishna-Godavari coastal tract (after Lakshminarayana et al. 1992)

Group		Formation	Lithology	Age
			Deccan Trap	
			---------- Unconformity ---------	
COASTAL CONTINENTAL	Upper Gondwana	Tirupati	Conglomeratic sandstone, ferruginous sandstone, micaceous sandstone, clay-clast bearing sandstone and claystone with *Ptilophyllum* flora and fossiliferous limestone (Infra-trappean)	Cretaceous
		Raghavapuram	Greyish white to bluff shale, carbonaceous siltstone and micaceous sandstone with *Ptilophyllum* flora, palynofossils and invertebrate fauna	
			--------- Unconformity ---------	
	Upper Gondwana	Kota	Conglomeratic sandstone, clay-clast bearing sandstone, variegated claystone with *Ptilophyllum* flora	Jurassic
			--------- Unconformity ---------	
	Lower Gondwana	Kamthi	Conglomeratic sandstone, ferruginous sandstone and claystone with *Glossopteris* flora	Upper Permian to Lower Triassic
			-------Unconformity/fault -------	
			Khondalite	Precambrian

Callialasporites sp. *Lycopodiumsporites* sp., *Impardecispora* sp., and *Concavissimisporites* sp. Among the plant fossils in the Raghavapuram Formation are *Ptilophyllum acutifolium, P. cutchense, Taeniopteris spatulata, Otozomites* sp., *Pterophyllum* sp., *Cladophebis clentialata* and *Araucarites cutchensis*. Foraminifera characterised by *Haplophragmoides* and *Ammobaculites* suggest an Early Cretaceous age.

Tirupati Formation: This formation conformably overlying Raghavapuram Formation and sometimes overstepping on to the khondalites of the Precambrian, is met with in the Gopalapuram-Buchayapalem-Duddukuru area of West Godavari district, Andhra Pradesh. It is made up of conglomerates, conglomeratic sandstones and sandstones of prograding delta. The plant fossils recorded from this formation are: *Marattiopsis macrocarpa, Gleichenites gleichenoides, Dichoteris elorensis, Dictyozamites indicus, Ptilophyllum acutifolium, Nilssonia morrisiana, Elatocladus* sp., *Podozamites lanceolatus*.

A horizon of 1m thick fossiliferous limestone at the top of the Tirupati Sandstone, south of Duddukuru, characterised by the presence of *Turritella, Cardita beaumonti, Nautilus, Lunulites* and *Chelae* of crab etc., originally considered to be infra-trappean, since it just underlies a flow of the Trap (Deccan Trap), is now thought to be the topmost unit of the Tirupati Formation. These beds represent delta abandonment phase in late Cretaceous. Therefore, the Raghavapuram and Tirupati Formations together denote a Cretaceous delta cycle.

The change from continental Gondwana to coastal Gondwana is considered to have taken place in the following four stages:

Stage I: Sediments in a north-westerly flowing system (Late Carboniferous – Early Jurassic)

Stage II: Westerly shift in palaeocurrents attributed to an obstruction caused by an upliftment of the Mailaram high parallel to NE-SW Eastern Ghats trend

Stage III: Deltaic sedimentation towards east (Early Cretaceous separation of landmass)

Stage IV: Basement uplift and delta progradation

A NE-SW Kallacheruvu-Zangareddigudem ridge is considered to have prevented marine incursion from the southeast into the Godavari graben, during the deposition of Raghavapuram Formation.

It is suggested that the changeover from continental Gondwana to coastal Gondwana had occurred over a time span of about 70 Ma between Late Jurassic to Cretaceous and controlled by phase-wise upliftment of the basement as a corollary to the Gondwana continental break up. The contact zone between the intracratonic Godavari rift and the Krishna–Godavari Coastal tract defines the Godavari Triple Junction (Figs. 7.6 and 7.7). The sedimentary transition pattern between the continental Gondwana and the coastal Gondwana reflects the pattern of the continental break up.

Vejendla-Vemavaram Formations: In Vejendla-Vemavaram area of Guntur and Prakasam districts of Andhra Pradesh, the so-called Budavada and Pavalur Sandstones occur as disconnected lensoid units in a monotonously thick sequence of Vemavaram Shale. These sandstones laterally grade into the shale. Bruce Foote had originally classified the Gondwana sediments of this area into Budavada Sandstone, Vemavaram Shale and Pavalur Sandstone. These are now classified as Vemavaram Formation (with intercalations of sandstones) and Vejendla Formation. Vemavaram Formation contains fossil assemblage

(flora and fauna) with Upper Gondwana affinity. The fossils include *Ptilophyllum* sp., *Dictyozomites* sp., *Dicroidium* sp., *Williamsonia* sp., and mollusca *Inoceramus* sp., *Mytilus, Nautilus* sp. and fish impressions.

There are outliers of Upper Gondwana in Jaggampeta, Simhadripuram, Ayyaparaz-Kottapalle, Gunupudi and Gurrajupeta in the northern part of coastal Andhra Pradesh. They are represented by pebble to boulder-conglomerate overlain by sandstone. They are seen up to 80 m above msl. Upliftment due to neotectonic movements along lineaments during the Quaternary is suggested for their position here.

Palar Basin (Tamil Nadu)

The Palar basin lying close to Chennai (formerly Madras) city in Tamil Nadu extends over a distance of about 125 km, the maximum width being about 20 km. The basin extends a little into Andhra Pradesh also to its north. Within the basin, the Gondwana sediments occur as three distinct patches from north to south, including the Sriperumbudur-Satyavedu, the (former Conjeevaram) Kanchipuram-Kattavakkam and the Uttiramerur-Madurantakam areas. The stratigraphy of the Palar basin is given in Table 7.7.

The assorted boulders present in the Talchir argillaceous siltstone in onshore Palar basin in Chengalpet district, Tamil Nadu are probably morainic blocks carried by icebergs that floated on a proglacial lake basin. Hence the environment could have been glacio-lacustrine. Greenish grey argillaceous siltstone in the Lower Gondwana sequence may be indicative of the same.

Table 7.7. Classification of strata in Palar Basin (after Natarajan and Kumaraguru, 1996)

	Formation	Lithology	Age
	Satyavedu	Conglomerate Sandstone Conglomerate	Upper Jurassic (?)
Upper	---	---	
Gondwana		Shale	Middle Jurassic (?)
	Sriperumbudur	Sandstone Conglomerate	
	---	---	
Lower	Talchir	Green Shales	Upper Carboniferous
Gondwana		Boulder Beds	
---	---	---	---
Cuddapah	Nagari quartzites		Proterozoic
Supergroup			
---	---		---
Peninsular	Granites and		Archaean
Gneiss	Gneisses		

During the Late Carboniferous and Permian the Palar basin is considered to have existed between 60 and 70° south palaeolatitudes. It is in the Uttarameruru-Madurantakam area that Talchir sediments of glacial origin were met with. Boreholes at Kattavakkam and Orikkai around Conjeevaram in Palar basin yielded a palyno–assemblage, which with the exception of *Cyclobaculitesporites* and *Microbaculitispora* is highly characteristic of Talchir Formation and confirms unequivocally the occurrence of Talchir sediments in Palar basin.

Good sections of Sriperumbudur Formation are seen near Pundi along the banks of Kortalayar River and also in Odappi in Tiruvallur district, Tamil Nadu. *Pascoites crassus* (ammonites), and *Haplophragmoides* and *Spiroplectammina* (forams) are reported from here and as a whole suggest a Lower Cretaceous age indicating Upper Gondwana.

Satyavedu Formation is named after Satyavedu village in Chittoor district in southern part of Andhra Pradesh. This formation consists of ferruginous sandstone and conglomerate characterised by the presence of pebble to boulder size clasts of Cuddapah (Nagari) Quartzite and Precambrian crystalline basement located to the west.

Trichy Area

The Sivaganga Formation is divisible into three members namely Kovandakaruchi conglomerate, Kovandakaruchi siltstone and Terani Clay member. The conglomerate is pink to buff and made of sub-angular to sub-rounded pebbles and cobbles derived from the Precambrian gneissic basement located in the west. The conglomerate is cast supported in the lower part, matrix supported in the middle, and grades into pebbly sandstone in the upper part. The siltstone is off-white to light grey, parallel bedded and made of fining upward couplets of siltstone/sandstone and silty clay. The Terani Clay is made of white to grayish white clay and silty clay containing an ensemble of invertebrate fossils viz. bivalve (*Inoceramus* sp.) and ammonoids and plant fossils viz. filicales, cycadophyta and conifers of *Ptilophyllum* flora and of Barremian (early Cretaceous) age. A ferruginous clay bed marks an unconformable contact between the Terani Clay and the overlying middle to late Cretaceous Uttatur Stage of the Cretaceous succession of Trichinopoly area.

Ramanathapuram

The southernmost Gondwana outcrops known so far are met with in Sivaganga district of Tamil Nadu in the Sivaganga-Tirupattur area. The

sediments consist of boulder beds and conglomerates at the base, followed by micaceous sandstones, grits and shales. These are called Sivaganga Beds and the important plant fossils in them are: *Cladophlebis lobata, Taeniopteris spatulata, Ginkgoites crassipes, Brachyphyllum expansum, Elatocladus plana, Podozomites lanceolatus* etc. These are considered to be Neocomian to Aptian (Lower Cretaceous) in age.

Coastal Gondwana Formations have yielded plant and marine fossils which indicate (i) time of marine transgression within Gondwana and (ii) palaeo-ecology and sedimentation history. The ammonites (*Pascoeites crassus, P. budavadensis, Australiceras jacki*), the lamellibranches (*Ostrea* sp., *Inoceramus* sp., *Tellina*,) and palynoflora indicate an Aptian age.

WEST COAST

Kutch (Gujarat)

The Umia Series conformably overlies the Katrol 'Series' and is made of sandstone, conglomerate and shale. The Series was earlier divided into three members namely Umia, Ukra and Bhuj. The Bhuj member is characterized by the presence of *Ptilophyllum* flora and the early Cretaceous palynofossils (see page 703 under Cretaceous in Chapter 8).

GONDWANA IN EXTRA-PENINSULAR INDIA

Kashmir

The earliest plant bed of the Lower Gondwana affinity, lying at the base of the Panjal Trap in Kashmir is designated as Nishatbagh Bed. The beginning of this bed marks the emergence of the continental phase in Kashmir during the early part (not earliest) of the Artinskian stage (Early Permian). Five distinct plant horizons at different levels are reported. The formations are already listed under the Permian Gondwana in an earlier chapter and the sequence is given therein (Table 6.7).

The Nishatbagh Bed is separated from the Mamal Formation by volcanic flow and inter-trappeans. The Mamal Formation subdivided into Risin, Marhom, Mund and Dunpathri Members is separated from the overlying Zewan Formation containing Upper Permian marine strata by a disconformity and a fault.

Dark coloured tuffaceous shale is the main constituent of the Nishatbagh Bed. The plant fossils in this bed include: *Gangamopteris kashmirensis, G.angustifolia, Glossopteris longicaulis, G. nishatbaghensis, Psygmophyllum haydeni, Cordaites hislopi, Samaropsis.*

The Mamal Formation is mainly composed of tuffaceous suite of rocks, stratigraphically positioned between older Panjal volcanics and younger Zewan Formation. The members developed concurrently in lagoonal or lacustrine environments during the Panjal Volcanic extrusive episode. The plant fossils in this formation included *Paraspenophyllum, Trizygia speciosa, Lobatannularia ensifolia, Rajahia mamalensis, Glossopteris intermittens, G. feistmantelli, G. sahni,* and *Ginkgophyllum haydeni.*

These non-marine sedimentary deposits of Early Permian in Kashmir with characteristic Gondwana elements were originally termed as Gangamopteris Beds, but later as Lower Gondwana. These were considered to be local representatives at the northernmost frontier of Gondwanaland of the peninsular Lower Gondwana of Talchir-Damuda. Since all of the beds here belonged to Permian, they have been also called Permian Gondwana.

These beds contain the following plant fossils: Lycopod stem, *Lepidostrobus kashmirensis, Kawizophyllum dunpathriensis, Pecopteris, Kashmiropteris meyenii.* These show similarity with those of Cathaysian flora. All these are referred to Early Artinskian to Early Kungurian age (Middle Permian). A change from cool to warm and humid climate is considered to have prevailed during this period in Kashmir. The invertebrate fossils reported from the Gangamopteris Beds are: *Prognoblattina columbiana, Gondwanablatta, Kashmiroblatta marhomensis.* The vertebrates are *Amblypterus kashmirensis, Paleoniscus, Archaeogosaurus ornatus, Actinodon risinensis,* and *Chelydosaurus marhomensis.*

The first Gondwana insect from India, *Gondwanablatta reticulata* was reported from Gangamopteris Beds of Khunmu by Handlisch (1906-08).

Assam

The Permian Gondwana outcrops in Assam are scarce and localised at Singrimari in the Goalpara district. The area is to the north of Dolungmukh in Dhemaji district, where the Miri Formation of Lower to Middle Palaeozoic age is exposed. The Gondwana part is considered to be of Lower Permian age.

Some Gondwana rocks are supposed to be present all along the Himalayan foothills, from Arunachal to North Bengal, in the thrust belt north of the Siwalik, and their equivalents. These could therefore be easily present in Assam in block-faulted troughs within the basement areas buried under the Upper Mesozoic to Holocene sediments. 135 m of continental Permian sediments encountered at a depth of 1598 m in ONGC's Barapathar Well in the Dhansiri Valley probably represents subsurface occurrence of the Gondwana. The palynological assemblage indicates a Late Carboniferous to Permian age.

Arunachal Pradesh

An east-west trending belt of discontinuous outcrops of the Gondwana rocks is seen between Kameng in the west and Siang in the east. The Cenozoic Siwaliks in the south and Early Palaeozoic metasediments in the north, along prominent thrust planes, bound the Gondwana belt. The continental facies of Gondwana Group in Arunachal Himalaya is made up of sandstones, siltstones, shale and impersistent coal lenses. The shale has yielded rich floral assemblages represented by *Glossopteris, Gangamopteris, Vertebraria* etc. and are commonly recorded in the Kameng and Subansiri districts. In Subansiri district, highly vesicular and amygdaloidal basalt is observed in association with the Gondwana rocks, pointing to a basic volcanic event during the Lower Permian in this part of the Himalaya. Associated with the sandstones are highly weathered nodular shales, diamictite that have yielded well preserved marine invertebrate fossils such as brachiopods, gastropods, cephalopods, crinoids, bivalves and bryozoans of Lower Permian age. The brachiopods show dominance over other groups of fossils while the bivalves have maximum variety of forms.

ENVIRONMENTS OF DEPOSITION

When tillites and striated pavements were discovered indicating glacial action during Lowest Permian (Asselian), it was generally presumed that these may be the results of continental glaciation, similar to features left over by the retreating lobes of Pleistocene glaciation in northern parts of North America and Europe. However, later detailed studies showed that the Talchir glaciers were derived from ice caps on certain highlands. The initial glaciogene deposits were those left by retreating glaciers. The massive tillites were those brought in by meltwaters. All these are usually close to the then existing highlands. During this period, certain sections had intermixture of sandstone, siltstone and shale resulting from fluvial agency, while in others, not many though, there were marine intercalations, which contained a few important invertebrate fossils, which had relatively short geological range, thus aiding fixation of age of the associated sediments. The green shales of Talchir were followed by cross-bedded channel sandstone locally associated with carbonaceous shale. Figure 7.10 shows a possible scenario of the depositional environments as interpreted in the formations from Talchir to Supra-Panchet.

The Gondwana basins expanded spatially. The sedimentation is to be confined to three major belts of Koel-Damodar, Son-Mahanadi and Pranhita-Godavari basins. The sediments were essentially fluvial deposits. The geometry and lithological content of the strata indicate that they were essentially river channel sand bodies, floodplain and over-bank deposits. It is the development

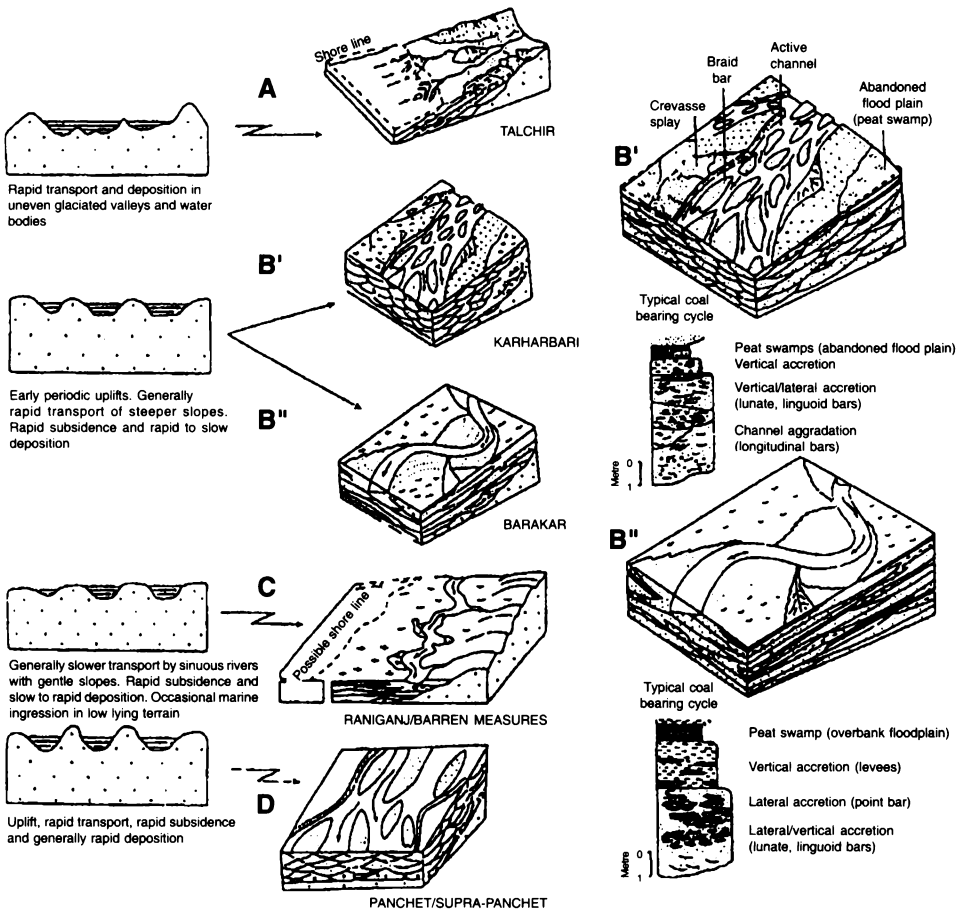


Fig.7.10. Block diagram and profiles of depositional environments of (**A**) Talchir Formation, (**B**) Karharbari and Barakar Formations, (**C**) the Barren Measures and Raniganj Formations and (**D**) the Panchet and Supra-Panchet (Mahadeva) Formations, from Casshyap and Tewari (1988, fig.2). Typical coal bearing cycles and enlarged diagrams B' of the Karharbari Formation and B" of the Barakar Formation are from Casshyap and Tewari (1988, fig.17) (reproduced from Veevers and Tewari, 1995, Mem. 187, Geol. Soc. America, Reproduced with permission from the publisher, The Geological Society of America, Boulder, Colarado, USA © 1995 Geological Society of America. (source: Mahadevan, 2002, p.432).

of peat swamps in protected and low-lying areas of abandoned floodplains that ultimately gave rise to the coal seams. The multi-storey sandstone bodies denote deposition in braided river environment characterized by channel avulsion and incision of pre-existing floodplains. There are, however, many variations in the thickness of the sedimentary bodies and coal seams. This is attributed to differences in basin configuration, basin profile, which may be the result of syn-rift tectonism that controlled sedimentation pattern and basin development. Cyclic sedimentation, often found, reflects changes in the energy levels of the agents of deposition. Hiatuses reflect either periods of non-deposition or erosion of part of the deposited material, though these are not many within the individual Lower Gondwana basins. Changes in climate brought about changes in lithology, particularly during the Triassic, resulting in the conspicuous red bed horizons in sections of Upper Gondwana.

To sum up, broadly it may be said that Gondwana environment in Peninsular India commenced with a glacio-marine environment followed by a humid fluvial environment despite being punctuated by semiarid and arid climates, which continued until the close of Gondwana deposition.

PALAEOCURRENTS

Over the years, in different Gondwana basins, paleocurrent directions have been inferred based on study of exposed sections in *nallahs* (streams) and quarries. Regionally, there is a consensus that the major direction of flow of the fluvial system was from east to west in the Koel-Damodar basin and SE to NW both in the Son-Mahanadi basin and Pranhita-Godavari basin. Figure 7.11 shows some of the paleocurrent directions as inferred in these regions. However, in certain areas flow directions do not necessarily conform to this general trend. This may be due to interference from other local streams joining the main river from different directions. Nevertheless, a regional synthesis of palaeocurrent data of major Gondwana basins and the isolated outcrops in between, points to a major northwest flowing Gondwana alluvial drainage system which had its origin located somewhere in the southeast beyond the east coast of India i.e. in pre-break up Antarctica or Australia.

CLIMATE

Based on a study of palynoflora, six major compositions have been identified and further divided into assemblage zones that constitute stratigraphically distinct entities in Lower Gondwana (Table 7.8). Climatic variations in terms of temperature and humidity are inferred from the nature of the palynoflora and this is included in Fig.7.9.

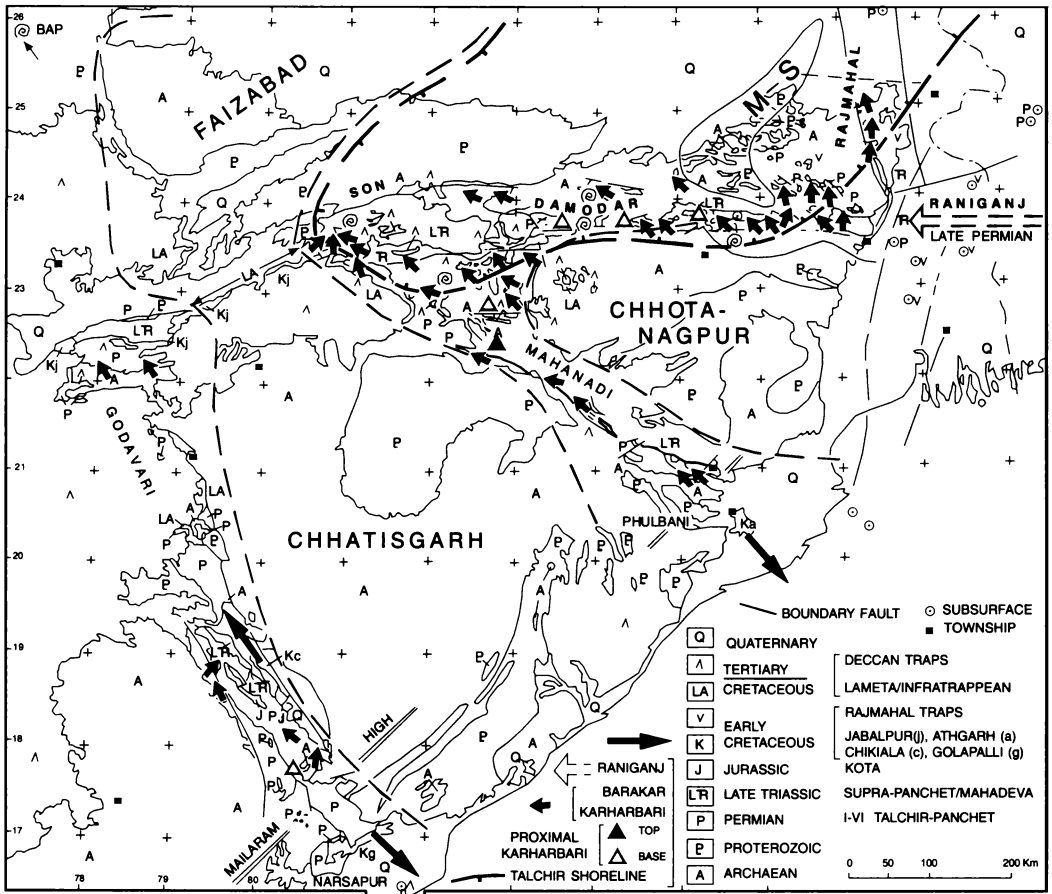


Fig.7.11. Gondwana basins of India, showing paleo-currents in the Early Permian Karharbari and Barakar Formations (short full arrows) of palynozones II and III (Tiwari and Tripathi, 1988), Later Permian Raniganj Formation (projected broken arrow) of palynozone V, and Early Cretaceous Athgarh, Chikiala, and Golapalli Formations (long full arrow). Marine invertebrates (coil) indicate the Early Permian (palynozone I or Tastubian) marine ingression towards the end of the deposition of the Talchir Formation that preceded the Karharbari and Barakar Formations. M-S: Monghyr-Saharasa (after Tewari and Veevers, 1993) (Reprinted with permission from Balkema Publishers).

Table 7.8. Palynoforms and Zones (Source: Mahadevan, 2002. p.397)

Composition VI	*Lundbladispora - Densoisporites* Zone	(D)
	Lunatisporites - Verrukosisporites Zone	(C)
	Verrucosisporites -Callumispora Zone	(B)
	Striatopodocarpites-Klausipollonites Zone	(A)
	Raniganj/Panchet Boundary	
Composition V	*Striatopodocarpites - Crescentipollenites* Zone	(D)
	Striatopodocarpites - Densipollenites Zone	(C)
	Striatopodocarpites - Gondisporites Zone	(B)
	Striatopodocarpites - Faunipollenites Zone	(A)
	Kulti/Raniganj Boundary	
Composition IV	*Densipollenites-Striatopodocarpites* Zone	(A)
	Barakar/Kulti Boundary	
Composition III	*Faunipollonites-Scheuringipollenites* Zone	(B)
	Scheuringipollenites/Faunipollenites Zone	(A)
	Karharbari/Barakar Boundary	
Composition II	*Parasaccites-Callumispora* Zone	(B)
	Callumispora-Parasaccites Zone	(A)
	Talchir/Karharbari Boundary	
Composition I	*Parasaccites - Plicatipollenites*	(B)
	Plicatipollenits-Parasaccites Zone	(A)

The glaciogenic character of at least the basal part of the Talchir Formation was first recognised by Blanford in 1856. Only two witnesses have been preserved to record the frigid phase of the Talchir glaciation, glacial pavements, and trains of exotic boulders. The glacial pavement occurs on the right bank of the Penganga River at Irai, near Chanda, Maharashtra. Striae have been incised on the pavement and are well preserved. Small patches of glaciated pavement are reported from the bank of Ajai River, north of Asansol, in West Bengal and along the northern fringe of Karanpura basin in Jharkhand.

Some of the Gondwana basins contain within them records of climatic changes indicating periods of deep weathering, physical and chemical, along with intense ground water activity. These have brought about palaeosols, which vary in thickness from 4 to 25 m characterised by red brown clay with mottles, rootlets, slickensides, ferruginous concretions and calcareous veinlets. Some of the pedogenic (palaeosol) and lateritic (latosol) profiles have been recorded, besides others, in the lower Barakar (early Permian) of Hutar basin of Koel valley, Barren measures (late Permian)- Sohagpur coalfield and Triassic/Jurassic contact of Rewa and Satpura basins.

COAL

The differences in the sedimentary composition and character of coal

seams can be attributed to differences in basin configuration, basin profile and their respective elements of syntectonism within and outside their basins. Out of the 2002 coal seam floors investigated in Indian Gondwana, only 10% has been found to be devoid of rootlets.

The preferred orientation in the long axis of plant fossils including *Glossopteris, Gangamopteris* and *Vertebraria* preserved in carbonaceous shale/siltstone lithofacies of Early Permian Barakar Formation from nine coalfields of east-central India (Raniganj, Jharia, Jainti, Sahajuri, East Bokaro, North Karanpura, Singrauli, Korba, Talchir) indicates drifted/transported nature of plant debris against in situ plant growth. The angular relationship of plant fossil orientation with the regional palaeoslope implies the deposition of fine clastic lithofacies in the overbank and flood plain subenvironments.

The conversion of higher plant material (vascular plants) from its original state after burial results in the progressive formations of humus, peat, brown coal/lignite, sub-bituminous coal, bituminous coal and anthracite. The processes of coalification involve an increase in fixed carbon and decrease in volatile matter. These processes are irreversible. Most of the coals in Lower Gondwana are bituminous to sub-bituminous coal. Anthracite is known from Tertiary coals in Assam subhimalaya and lignite in the Tertiary formations of Rajasthan and Tamil Nadu.

In a number of basins, particularly in the Damodar valley, dolerite dykes intrude into the sediments, and some of them have been displaced by later faults. Besides these, there are lamprophyre dykes and sills, which in a number of places, where they come into contact with coal seams, baked them rendering them useless. Locally these portions are called *jhama.*

The Gondwana formations including the coal have undergone intense metamorphism specially in the proximity of the thrust zone in the eastern and northeastern Himalaya. As a result the sandstones have been indurated, sheared, sheeted and boudinaged within carbonaceous shale. The coal seams have been crushed, sheared and rendered anthracitic and often they are highly weathered. They have also been rendered discontinuous and exhibit "pinch and swell" structure. As a result of tectonism the boulder slate unit and the quartzite-coal ensemble occur as thrust slices within the Palaeozoic/ Precambrian phyllites and quartzites. The coal in these parts have become unfit for exploitation.

CLASSIFICATION AND AGE

As already indicated earlier two-fold and three-fold classifications have been proposed for the Gondwana on the basis of floral evidence.

According to some, palynological evidences support a three-fold classification.

(i) The striatesaccate dominant flora of the Permian sediments, clearly distinguish the lowermost.

(ii) A major break at the Permo-Triassic boundary is evident and a rich trilete bearing spore flora together with the decline of the striate-saccate groups distinguish the middle division.

(iii) The uppermost division, on the other hand, is characterised by a distinct assemblage dominated by gymnosperm pollen.

Thus palynologically, a triparte classification is favoured, which plant megafossil evidences also seem to substantiate. This can be seen in the diagrammatic representation of the relationships between floras of Lower, Middle and Upper Gondwana presented in Fig.7.12.

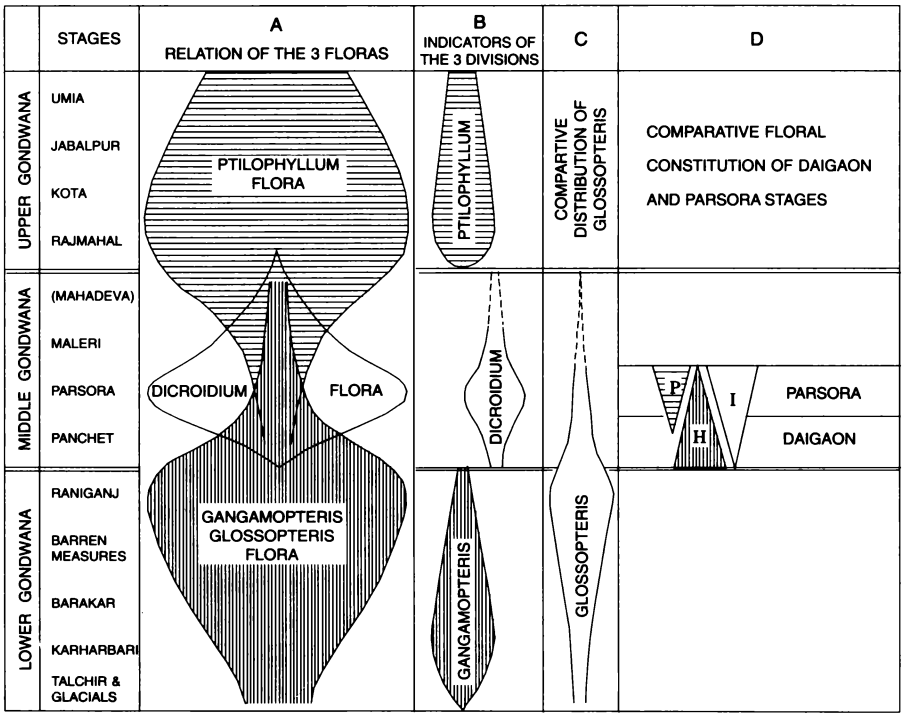


Fig.7.12. A. Semidiagrammatic representation of the relation between the floras of the Lower, Middle and the Upper Gondwana showing the overlap of the Permian 'Hold-overs' and the Jurassic 'Precursors' with *Dicroidium* in the Middle Gondwana times. **B.** Index plant genera of the three floras which serve to delimit the Lower, Middle and Uppler Gondwana divisions. **C.** Vertical distribution pattern of *Glossopteris* (as contrasted with *Gangamopteris*) showing its transgressive tendency and unreliability for delimiting the Lower Gondwana. **D.** Diagrammatic representation of the floral constitution of the Daigaon and Parsora Stages in terms of the so-called 'Hold-overs' (H), the so-called 'Precursors' (P) and the Index plant (I). (after Lele, 1964).

The basis for two and three fold subdivisions of Gondwana is lithological as well as palaeontological. It is rather because lithological boundaries seldom complement the palaeobotanical boundaries that the two schools of thought differ regarding the subdivision of Gondwana era.

Lithostratigraphic as also floral/faunal units are diachronous and their boundaries do not conform to each other. The floral changes in these intracratonic sequences even in a broad sense do not correspond even to standard period boundaries, not to speak of the stage, substage and zonal boundaries.

The Gondwana stratigraphic units have been formalised now as lithostratigraphic units, their distribution being based on lithology and other physical attributes. Whereas stratigraphic classification of strata and their ages have been presented already when dealing with individual basins, herein a classification is presented, which is one of the generally accepted classification of the Gondwana Supergroup of India (Table 7.1). It may be noted that no attempt is made to separate the Supergroup into Lower and Upper. However, traditionally the boundary between the Lower and Upper is placed above the Panchet Formation and its equivalents elsewhere, possibly because the basins in Damodar valley, where the formations have been studied first, contained an almost conformable stratigraphic sequence from Talchir to Panchet.

Gondwanaland existed at least right since Late Precambrian and continued as a single geographic unit until Permian i.e. for a much longer duration than the Indian Gondwana sequence itself.

While dating plant-bearing units, it must be done only with the help of short ranging index fossils or assemblages, based on precise data on taxa ranges; many fossil plants have wider ranges and therefore recourse is taken to fix the ages of the stratigraphic units within Gondwana based on other fossils or other lithostratigraphic criteria. Many marine elements provide a significant control on lithostratigraphic correlation.

GONDWANA IN SOUTHERN CONTINENTS

It was Alfred Wegner's forceful advocacy of Continental drift, later supported by many stratigraphic, palaeontological and physiographic evidences by du Toit and others, that firmly led to the recognition that at least up to the Permian the now separate parts of what was once Gondwanaland, were together. The mechanism that brought about the separation of the parts was not clear till the concepts of Plate Tectonics and Sea-floor Spreading came to the fore to explain the same.

A master basin has been conceived which had several common characteristics in the southern continents in parts of India, Australia, South

America, Antarctica, South Africa and Madagascar (Malagasy). Their characteristics include the presence of a basal glacial bed, presence of large coal seams, common fossils and an end-phase of volcanic eruptions, though these have not been closely contemporaneous. It is this extensive development that led to the concept of these continents having been a more or less closely connected large landmass, the Gondwanaland, a supercontinent that existed in the southern hemisphere.

Table 7.9 is an attempt to correlate the different stratigraphic horizons in some of the basins in the different continents of South America, Africa, Asia, Antarctica and Australia. During the past few decades more isolated basins within each of the continents have been discovered and stratigraphic sequence established. The association of workable deposits of coal in some of the horizons added impetus for the investigation into these sediments.

Just as in the case of Indian subcontinent, apart from the three basins of Damodar, Son-Mahanadi and Pranhita-Godavari containing sediments of Gondwana Supergroup, there are some far away in Kutch, Jammu and Kashmir and Arunachal Pradesh also containing sediments referred to Gondwana, similarly in South America apart from those in Brazil, deposits are in parts of Argentina, Uruguay, Paraguay and Falkland Islands. In South Africa, though Karoo represents the best exposures from those of Late Carboniferous to Late Triassic, rocks of similar nature are found in the Zambesi Basin and in countries like Angola, Tanzania, Kenya, Congo and Uganda. In Madagascar (Malagasy) both continental and marine sediments of Gondwana are reported.

Veevers and Tewari (in Fig.45, 1995) have attempted an excellent synthesis of tectonics and environments in different sections of Eastern Gondwanaland, bringing into perview glacial periods, coalification, volcanic episodes and life of the period from around 330 Ma to 163 Ma.

The numerous expeditions undertaken to Antarctica by scientists from different countries have resulted in the find of Gondwana sediments in many places in East Antarctica (Beaver Lake), Ellsworth Mountains, Penscola, and Queen Maud Land, besides Victoria Land. Whereas the major outcrops are in Eastern Australia, Gondwana sediments are also known from Tasmania and Western Australia.

With exceptions, the base of what is designated as Gondwana, invariably commenced with a glacial bed in almost all the southern continents, though not always exactly at the same time. There are marine intercalations in some. What is noteworthy, however, is that a detailed study of the formations belonging to the Gondwana in all the southern continents showed the existence of glacial, fluvial, aeolian, paludal, lacustrine and deltaic sediments besides volcanic flows and intrusives. Another feature was a general transition in climate from glacial to temperate to arid and back to semiarid, though it is not as if all of them

Table 7.9. Comparative (tentative) stratigraphic sequence in some of the major Gondwana sedimentary basins in southern continents

Ma.	Age	South America (Brazil)	South Africa (Karoo)	Madagascar (Malagasy)	Peninsular India	Antarctica (Victoria Land)	Eastern Australia	Ma.
Scale Change		Serra Geral Arapey Botueatu	Drakensberg (Stromberg)		Jabalpur		Dolerite flows and sills	
	Jurassic	Tacuarembo			Dubrajpur Kota			
				Isalo II		Lashly		
		Piramboia	Clarens				Wianamatta (Up. Ipswich)	
-220-								220
		Santa Maria	Elliot				Arenito	
	Triassic	Rosario do Sul/Yaguari	Molteno		Supra Panchet/Bagra		Hankesbury (Ipswich)	
		Rio do Rasto		Isalo I	Denwa/Maleri Pachmarhi			
		Estrada Nova			Panchet/Pachmarhi/	Feather	Narrabeen	
			Beaufort	Sakamena	Kamthi	Conglomerate		
-250-		Serra Alta					Singleton	250
		Irati			Raniganj/Bijori/			
	Permian	Palermo			Kamthi	Weller Coal	Upper Marine	
		Rio Bonito	Ecca		Barren Measures/			
		Tres Islas			Motur	Metshel	Greta Coal Measures	
					Barakar & Karharbari			
					Talchir		Lower Marine	
-300-	Late Carboniferous	Itarare	Dwyka	Sakoa				300
		Aquidauana					Upper Kuting	
		San Gregoris						

Data extracted from (i) Le Roux and Toens (1987); (ii) Veevers and Tewari (1995, Fig.45); M.S. Krishnan (1982, Table 38) and (iv) Mitra et al. (1977)

experienced the same climate at the same time. The variation in climate must have been mainly due to the fact of parts of Gondwanaland passing over different climatic belts during the migration of the plates containing them.

8

Mesozoic

INTRODUCTION

Mesozoic era extended for a much shorter time span of about 185 Ma (from around 250 to 65 Ma) compared to that of Palaeozoic era, which lasted for about 290 Ma. Supercontinents were fragmented and there were marine regressions during the Permian, increasing the land area. Subsequent marine transgressions in India apparently inundated larger areas during the successive periods of Triassic, Jurassic and Cretaceous. Marine Triassic was mostly confined to the Himalayan belt (Fig.8.1). During the Jurassic considerable deposition took place in the Higher Himalaya (Tethys) (Fig.8.2) and in the western sector in Kutch (also spelled as Kachchh in most of the recent publications) (Fig.8.3) and Rajasthan (Fig.8.5). During the Cretaceous, larger areas were covered in parts of Narmada basin in Central India and southeastern India, besides other places (Fig.8.4). Sedimentation was not continuous in all the above areas. There were a number of areas of hiatus within these periods depending upon regional tectonics and sea level changes. Mesozoic was almost free from any mountain building activities and only vertical movements (epeirogenic) affected the Mesozoic geological evolution of India. The Mesozoic sedimentation was, however, terminated by Late Cretaceous, ending in Deccan Trap volcanic activity.

The Higher Himalayan basins mostly received continuous sedimentation since the beginning of Phanerozoic or earlier. But those of the western and eastern sectors originated in successive impulses in response to initiation of rifting activity in India-Africa and India-Antarctica-Australia plate regions of the composite Gondwana superplate. In general the basin evolution began first in the western sector near the Triassic/Jurassic boundary, and proceeded from north to south. All the three periods of the Mesozoic era developed in different parts of Kashmir. In Jammu Himalaya only rocks of Triassic are exposed with the absence of Jurassic and Cretaceous; basins of Kutch, Jaisalmer, Ladakh, Spiti, Kumaon originated earlier than Cretaceous; Godavari, Krishna, Palar

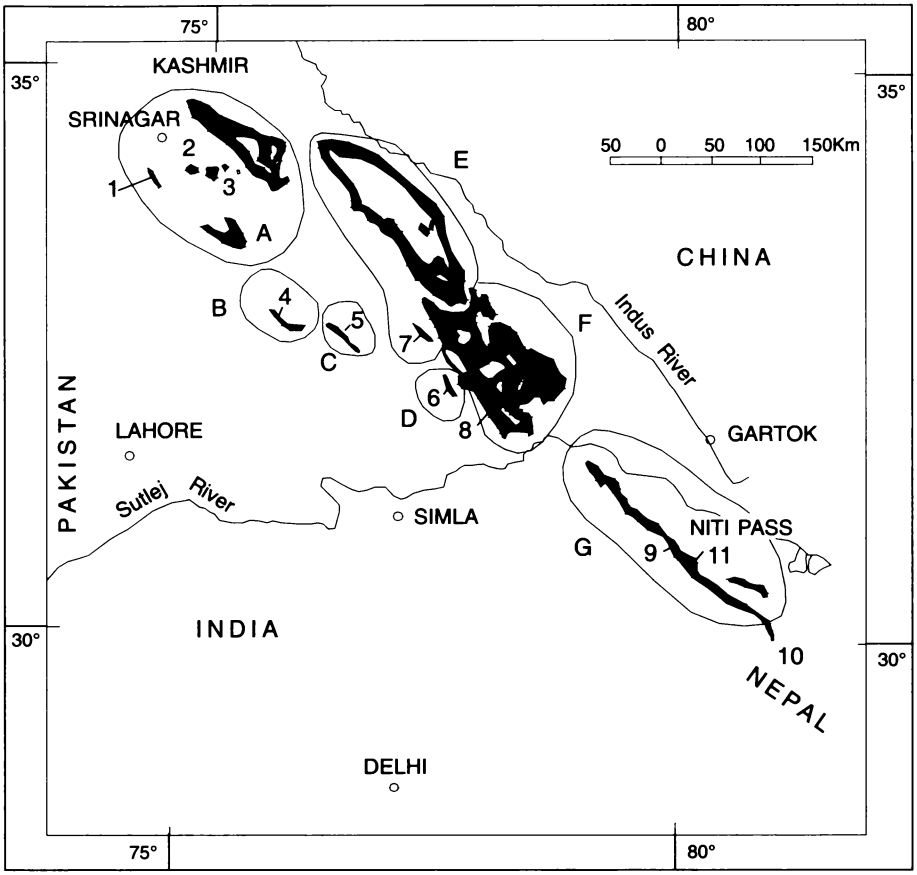


Fig.8.1. Distribution of marine Triassic of India. **A** - Kashmir region; **B** - Bhallesh region; **C** - Chamba region; **D** - Tandi region; **E** - Zanskar region; **F** - Spiti region; **G** - Central Himalayan region. **1** - Pir Panjal; **2** - Guryul ravine; **3** - Pastannah; **4** - Bhallesh; **5** - Kalhel; **6** - Tandi; **7** - Chharap; **8** - Lilang; **9** - Bambanag and Shalshal cliff; **10** - Tinkar Lipu; **11** - Exotic Blocks (after Kapoor, 1987).

and Cauvery originated near the Jurassic/Cretaceous (J/K) boundary, Cambay (Khambhat) and Narmada near the Albian/Cenomanian boundary and Assam basin near the Santonian/Campanian boundary. Arunachal Pradesh does not have any Mesozoic strata and perhaps stood as a landmass throughout this era.

Good exposures coupled with exploration for oil and natural gas for over three decades, have resulted in a wealth of data on the geology of the Kutch, Jailsalmer, Mahanadi, Krishna-Godavari, Palar, Narmada and Cauvery basins. In this chapter some of the important findings are highlighted.

Among the different basins in the western sector, the sediments of Mesozoic basins of Kutch and Jaisalmer range from Late Triassic to Early Cretaceous with some breaks in sedimentation. These enclose sediments of 1500-3000 m thickness in Kutch and about 800 m in Jaisalmer, covering

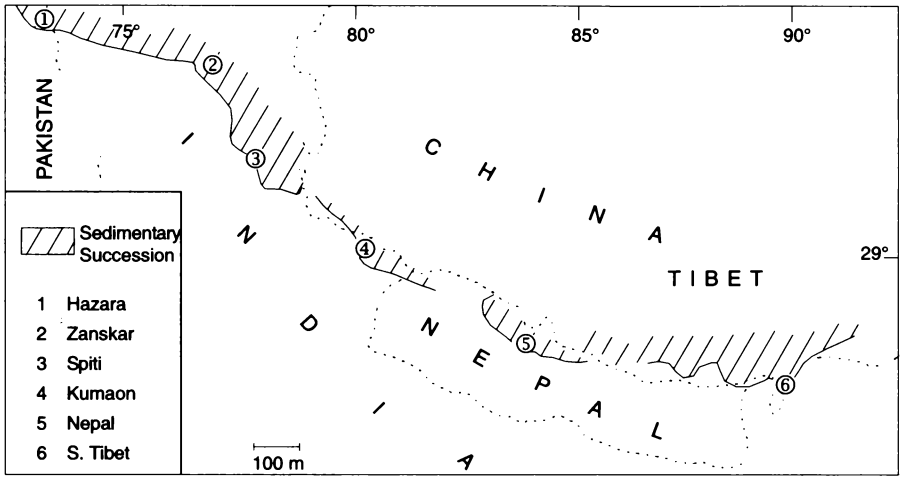


Fig.8.2. Main Jurassic-Cretaceous localities of the Tethyan Himalayan Belt (after Jai Krishna and Pathak, 1994). m: miles (scale).

43,000 km^2 of basin area, which include about 15,000 km^2 and 800 km^2 respectively of outcropping sedimentary areas. The Jaisalmer basin is a part of Indus Shelf whereas the Kutch basin is rifted along the major Precambrian lineaments in Western India prior to the fragmentation of the Gondwana superplate. The successions in both these basins are thick and exhibit a fair degree of stratigraphic similarity. The sediments, except for the Middle Jurassic carbonates, are dominantly siliciclastic. The lower part of the succession is marine and the upper part with plant beds is deltaic.

In Kutch, Mesozoic rocks ranging in age from Middle Jurassic to Lower Cretaceous are exposed in the following six disconnected highland areas: (i) Kutch Mainland (ii) Pachham "Island" (iii) Khadir "Island" (iv) Bela "Island"(v) Chorar "Island" and (vi) Wagad Highland (Fig. 8.3).

Wynne mapped Mesozoic rocks of Kutch. Stoliczka, Spath and Waagan studied the fossils. Waagan suggested the well known four-fold subdivisions of Patcham, Chari, Katrol and Umia in ascending order. Subsequently Rajnath (1932) studied the northwestern parts and modified the classification. It was Biswas (1971), however, who provided a comprehensive lithostratigraphic succession of Kutch Mesozoic, based on measured lithostratigraphic columns and detailed mapping done by ONGC. The importance of molluscan and ammonite fossils in the biostratigraphy of Kutch basin has been brought to light by many workers.

Mesozoic sedimentation in Kutch basin, in general, commenced with the deposition of retrogradational and aggradational succession (RS & AS) in the lower part during marine transgression followed by the progradational succession (PS) in the upper part during marine transgression. Transgression

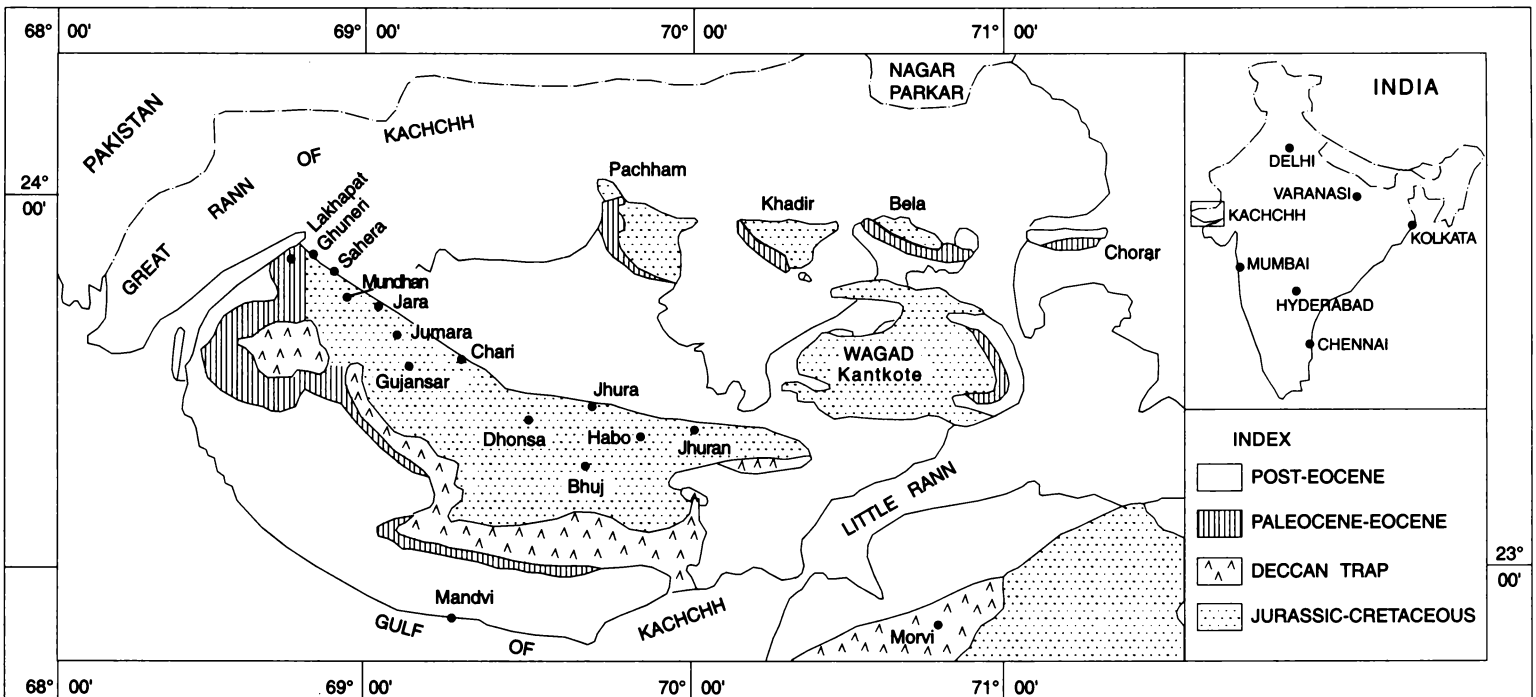


Fig.8.3. Geological map of Kachchh Basin (after Dubey and Chatterjee, 1997).

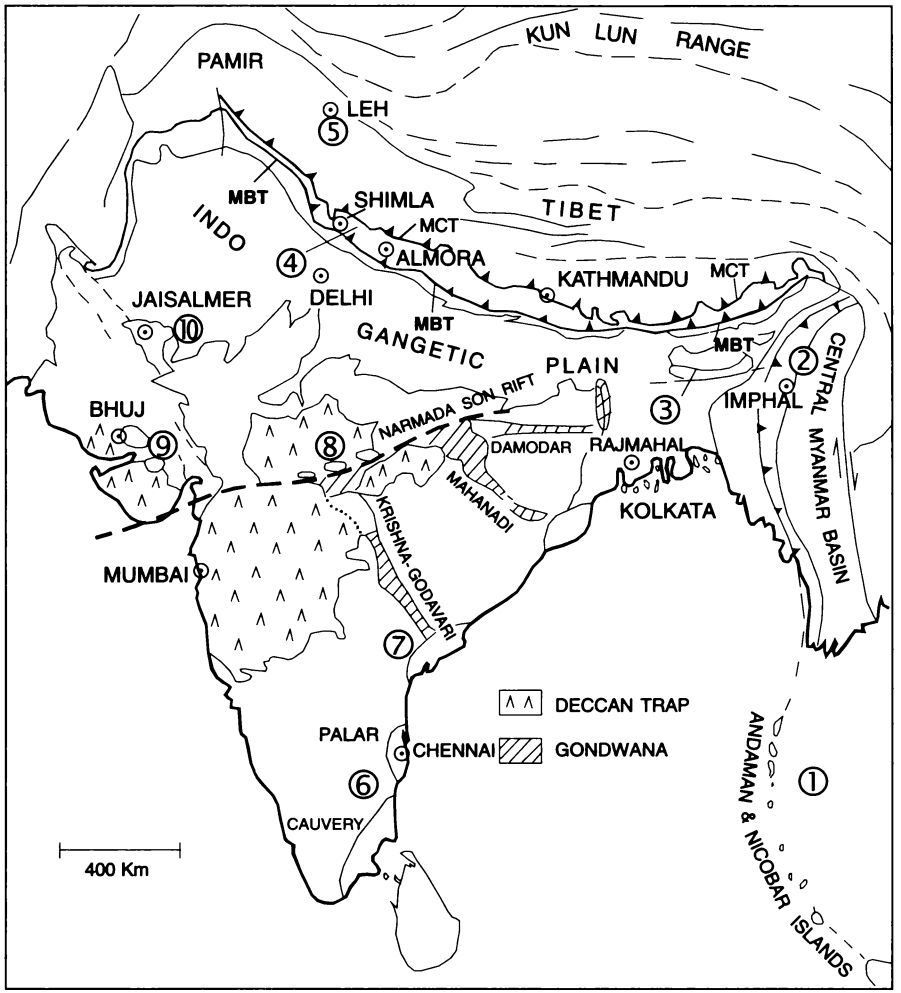


Fig.8.4. Sketch map of the Indian subcontinent showing major tectonic elements and the position of various marine Cretaceous basins. **1** - Andaman-Nicobar; **2** - Assam-Arakan; **3** -South Shillong; **4** - Lesser Himalaya; **5** - Tethyan Himalaya; **6** - Cauvery-Palar; **7** - Krishna-Godavari; **8** - Narmada; **9** - Kutch-Saurashtra; **10** - Jaisalmer. (after Jafer, S.A., 1996, p.123).

starts with Bajocian. RS and AS deposited during Aalenian-Tithonian, exhibit onlapping, thick highly fossiliferous limestones, shales and thin sandstones. AS deposited during Oxfordian is characterised by a sequence of fossiliferous, oolitic limestone/sandstones. PS deposited during Neocomian (?)-Albian dominantly represents sandy lithologies of coarsening upward, offlapping sandstones, shales and thin ferruginous beds. Qualitative and quantitative analyses of heavy minerals, quartz grains and lithic fragments suggest at least two lithologically different Precambrian provenances during Mesozoic, namely (i) the Aravalli Range of Rajasthan towards north and east and

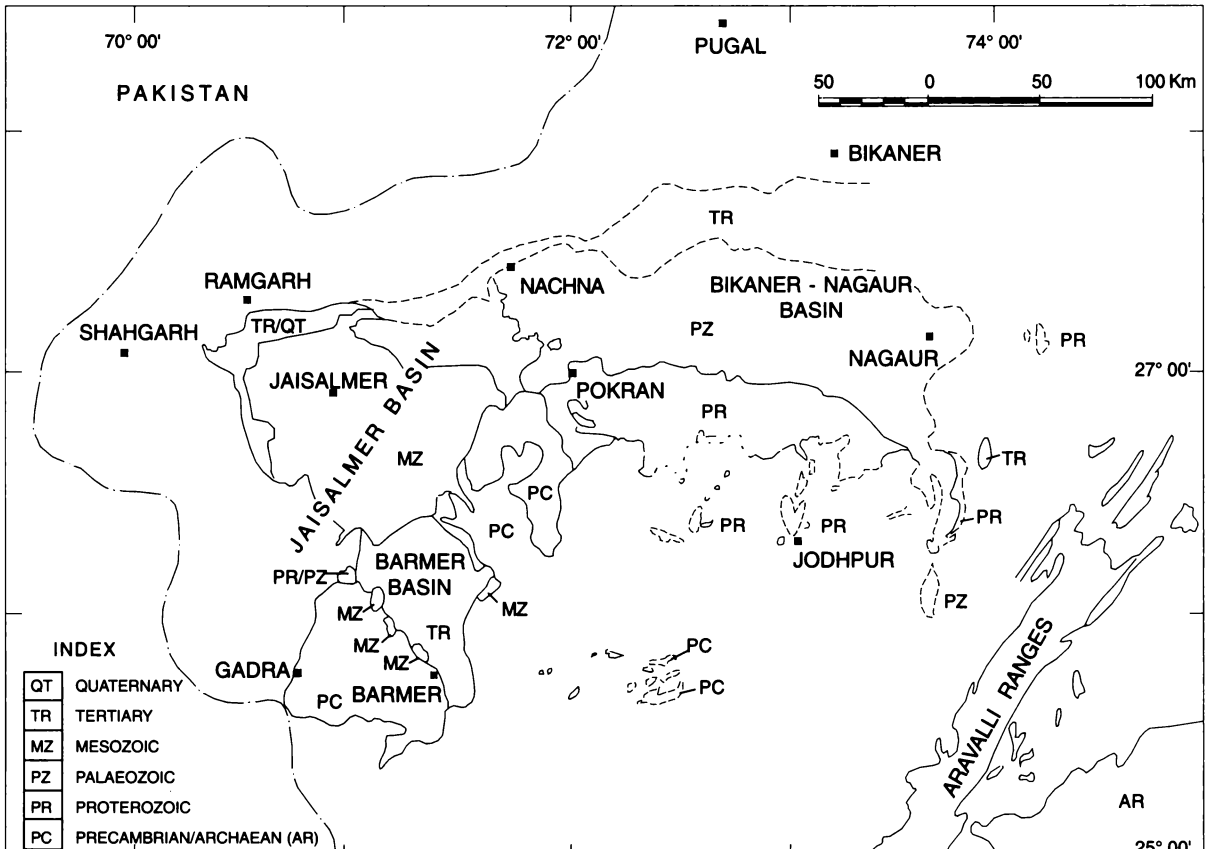


Fig.8.5. Index map: west Rajasthan basins (modified after Das Gupta, 1974).

(ii) the Nagar-Parkar massif (granites, syenites) towards north and northwest, in Pakistan.

The Mesozoic and Tertiary sequences in the Jaisalmer basin (Fig.8.5) represent typical shelf zone sedimentation of orthoquartzite-limestone association resting on a peneplained Precambrian surface. The sedimentation started from Lias with deposition of the continental Lathi Formation. This is overlain by carbonate rocks of Jaisalmer Formation (Callovian-Oxfordian) and shaly Baisakhi Formation (Kimmeridgian), together representing the first marine transgression. The overlying Bhadasar Formation (Tithonian) represents the regressive phase, which is succeeded by the deltaic Pariwar Formation (Neocomian). The second marine transgression is represented by the Habur Formation (Aptian) on the surface, while in the subsurface this is represented by the Parh (Turonian to Coniacian) Formation. The Sanu Formation (Lower to Middle Paleocene) represents regression of the sea but the upper part of Sanu and subsequent Khuiala (Upper Paleocene to Ypresian) and Bandah (Lutetian) Formations represent the third marine transgression. Thereafter marine conditions appear to have completely receded from the Jaisalmer basin.

W.T. Blanford carried out the first systematic survey of the Tapti and the Narmada valley rocks. It was Chiplonkar who initiated a number of studies on the stratigraphy and fauna of the Narmada basin. The Narmada basin contains only a part of the Cretaceous, namely from Albian to Turonian, in the Bagh beds, which are followed by Lameta Formation of Upper Cretaceous. The former were marine to start with, but later fresh water conditions prevailed ultimately leading to essentially fluviatile deposition of Lameta, which subsequently underwent pedogenic modifications.

It was H.F. Blanford who mapped the exposed Gondwana and Cretaceous formations of the Trichinopoly area in Tamil Nadu and it was Stoliczka and F. Kossmat, who contributed substantially to our knowledge of the variety of fauna in these formations. The exposed Cretaceous shelf succession in Cauvery basin, in southeastern India, was a result of deposition in shallow marine conditions, open to ocean through most or all of its history.

A wide variety of Mesozoic basaltic and alkaline igneous rocks crop out on the eastern margin of the Indian shield, in Meghalaya-Nagaland. The K-Ar isotopic ages of these samples lie between 149-107 Ma, i.e., Late Jurassic to Early Cretaceous. Data on the tectonic setting and petrology of the basaltic and alkaline rocks suggest that their emplacement was controlled by major fault systems. Active mantle upwelling in an extensional tectonic regime related to the fragmentation of the Indian plate from the Australia-Antarctica plate in the Early Cretaceous, appears to have been the main trigger for the magmatic activity.

FAUNA AND FLORA

Invertebrates

During this era among the invertebrates, ammonoids dominated the seas. Cephalopods, exclusively marine in nature, and though present in the Palaeozoic, attained their maximum development during the Mesozoic era and a few of them continue in modern seas (Nautilus, cuttle fish and Octopus). The shape of the shell, the nature of coiling, shape of the aperture, position of the siphuncle and ornamentation over the shell aid in classifying the ammonoids, and provide clues to the environments in which they thrived. The suture lines, particularly, are of great diagnostic value in the classification of the cephalopods. In general, they slowly became complex with passage of time from Triassic to Cretaceous (Fig.8.6). While coiling of the shell underwent a progressive change to tight "coiling" (anagenesis) and was followed by "uncoiling" (catagenesis), a similar development did not happen in the geometrical pattern of the suture lines. The suture lines are manifestations of the junction of the edges of the septa (chamber partitions within the shell) and the interior wall of the chambers. The cephalopods, especially the ammonoids, have been used extensively in the

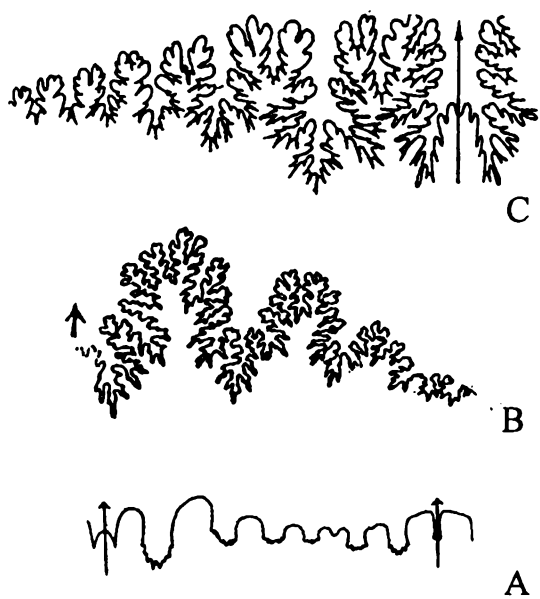


Fig.8.6. Representative septal sutures of Mesozoic ammonoids. (**A**) Triassic: *Otoceras woodwardi* with rounded saddles and serrated/dented lobes; (**B**) Jurassic: *Macrocephalites* sp. with highly frilled and complicatedly and repeatedly divided saddles and lobes and (**C**) Cretaceous: *Desmoceras latidorsatum* with still more finely frilled and repeatedly divided auxiliaries in characteristic descending order (arrow on the mid-venter directed adorally) (Courtesy: Jaikrishna).

detailed stratigraphic classification of the Mesozoic strata in India, particularly in the Triassic of Himalaya, Jurassic of Kutch and Cretaceous of Trichinopoly (Plate 8.1). Ammonoids and other invertebrates in splintery black nodules picked up from Himalayan river beds have been for ages considered by the Hindus as sacred symbols of the Lord Creator (Saligram).

Besides the cephalopods, many others among the invertebrates thrived in the marine waters of the Mesozoic (Plates 8.2 and 8.3). Brachiopods receded into the background except for terebratulids. Though bivalves, rhynchonellids and gastropods were in large numbers, their utility in correlation was confined only to a few specific areas and that too in the Cretaceous. Conodonts continued to be present in the Triassic and some bryozoans in the Jurassic and Cretaceous. Echinoderms were fairly well represented in Jurassic and Cretaceous, and became prolific in Early Cenozoic. Corals continued to form bioherms. Foraminifera increased in numbers and more than one hundred planktonic foraminiferal species have been identified from various Mesozoic sequences developed in India. Unicellular planktonic plants, diatoms and coccoliths made their first appearance during the Mesozoic.

Microfossils and palynofossils are used extensively in correlation of Mesozoic strata. The vertebrates, particularly the sauropods are used in reconstructing the palaeogeography of the region in relation to other parts of the earth's surface.

Notably, perhaps it is the collection of 148 species of ammonites, trilobites, corals etc. housed in the British Museum of Natural History, that inspired Eduard Suess to float the concept of ancient Tethys, possibly comparing the Indian collections with the Alpine ones, with which he must have been more familiar.

Conodonts are among the most important fossils of the Triassic. Though these have been recorded right from Cambrian, particularly from Kumaun-Garhwal, they have been mostly described from Permian and Triassic. These are minute, phosphatic, tooth-like or plate-like spiny microfossils considerably resistant to much chemical and physical destruction. Once regarded as palaeontological enigma, they have now been proven to be remarkably valuable in biostratigraphy and correlation on account of their easy recovery and identifiability and rapid evolutionary diversification leading to a greater variety of characteristic forms. They are found widely distributed in rocks from Cambrian to Late Triassic. Their tiny size and resistance to weathering have made them a precise tool for correlation. They possess many of the characteristics of good index fossils.

Vertebrates

The Mesozoic era is also called the "age of the reptiles." Actinoptererigian

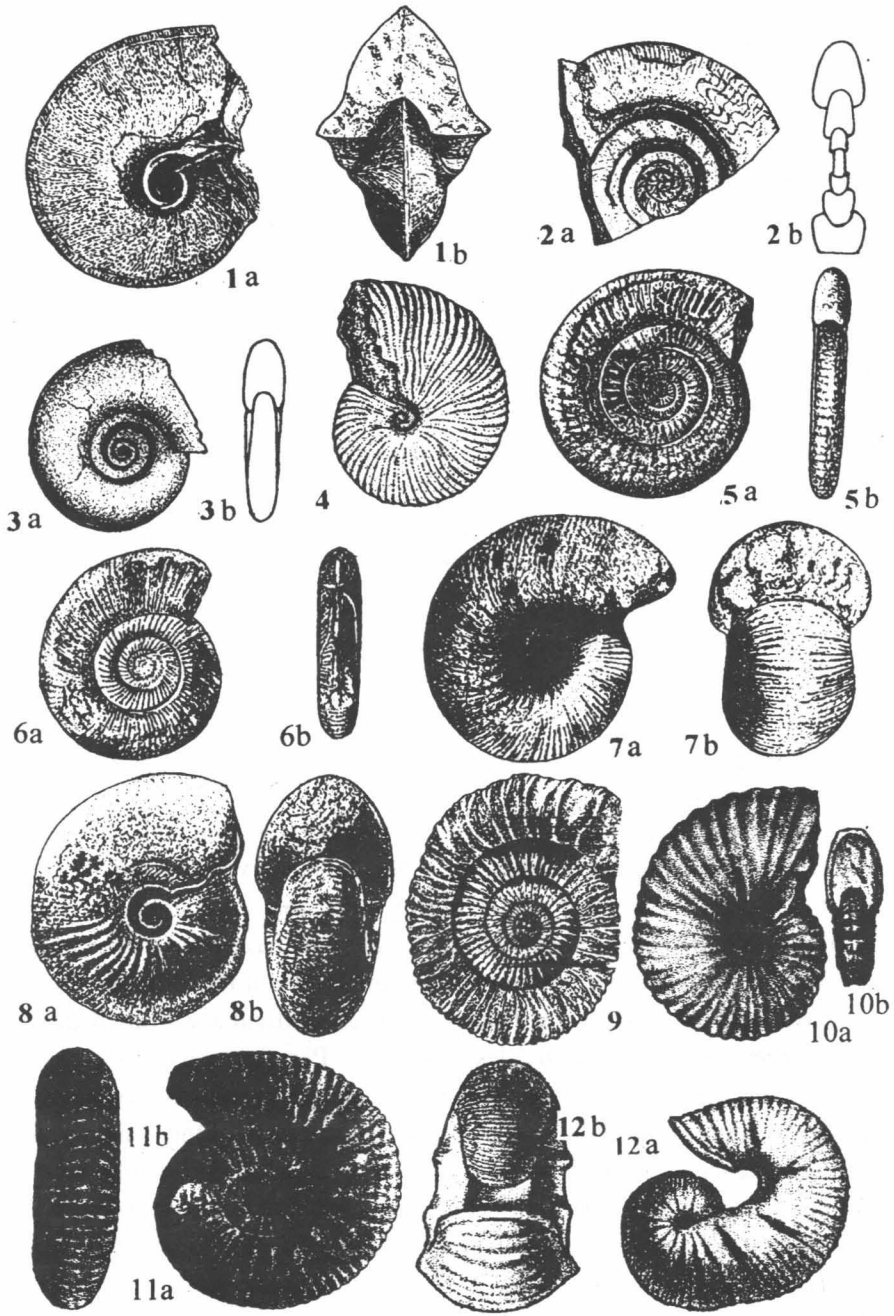


Plate 8.1. 1a-b. *Octoceras woodwardi* (Lower Triassic); **2a-b.** *Ophiceras tibeticum* (Lower Triassic); **3a-b.** *Gymnites incultus* (Middle Triassic); **4.** *Indoclionities gracilis* (Upper Triassic); **5a-b.** *Psiloceras planorbis* (Lower Jurassic); **6a-b.** *Leptosphinctes pseudomartinisi* (Middle Jurassic); **7a-b.** *Macrocephalities diadematus* (Middle Jurassic); **8a-b.** *Mayaites maya* (Upper Jurassic); **9.** *Katroliceras katrolensis* (Upper Jurassic); **10a-b.** *Utaturiceras vicinale* (Cretaceous); **11a-b.** *Argentiniceras lonochensis* (Lower Cretaceous); **12a-b.** *Scaphites equalis* (Cretaceous). (Courtesy: Jaikrishna and A.K. Jaitley).

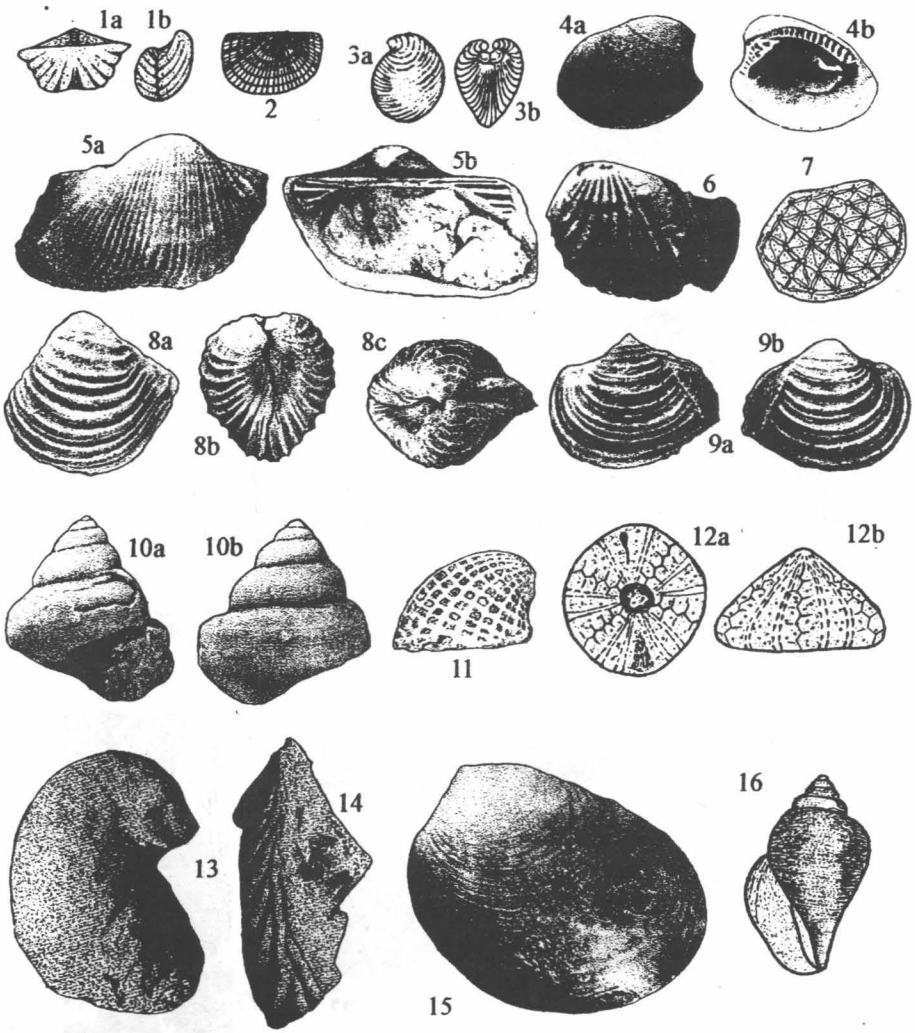


Plate 8.2. 1a-b. *Spiriferina stracheyi* (Middle Jurassic); **2.** *Daonella indica* (Middle-Upper Triassic); **3a-b.** *Megalodon ladakhensis* (Upper Triassic); **4a-b.** *Nuculom wynnei* (Middle Jurassic); **5a-b.** *Grammatodon virgatus* (Middle Jurassic); **6.** *Eligmus rollandi* (Middle Jurassic); **7.** *Stylina paruvla* (Upper Cretaceous); **8a-c.** *Indocerbula lyrata* (Middle Jurassic); **9a-b.** *Protocardia grandidieri* (Middle Jurassic); **10a-b.** *Bathrotomaria kachchhensis* (Middle Jurassic); **11.** *Eomarginula jumarensis* (Middle Jurassic); **12a-b.** *Stigmatopygus elatus* (Upper Cretaceous); **13.** *Ceratostreon pliciferum* (Upper Cretaceous); **14.** *Rastellum pectinatum* (Upper Cretaceous); **15.** *Seebachia sowerbyana* (Jurassic); **16.** *Physa prinsepii* (Upper Cretaceous). (Courtesy: U.B. Mallikarjuna and A.K. Jaitley).

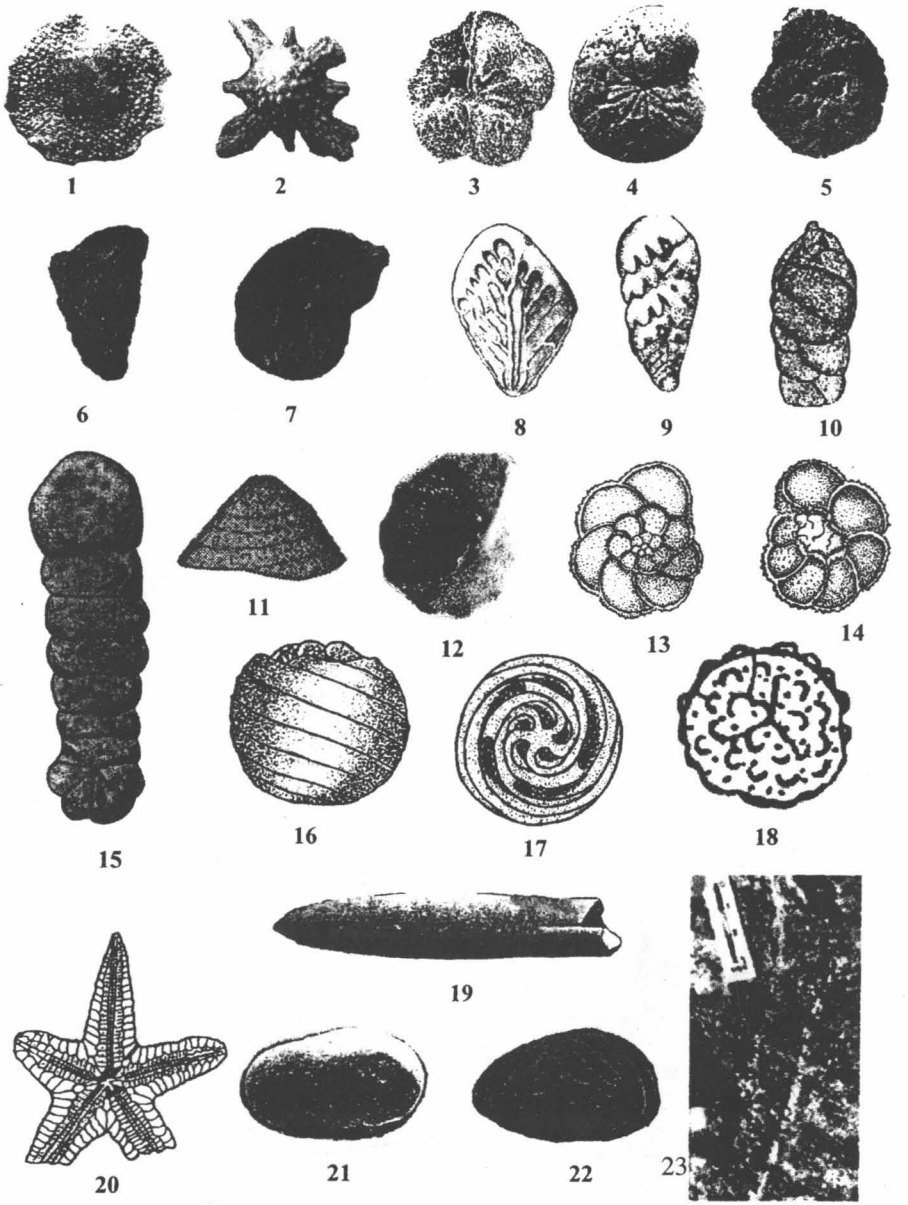


Plate 8.3. 1. *Lepidorbitoides* sp. (Upper Campanian-Lower Masstrichtian); **2.** *Siderolites cacitropoides* (Upper Campanian-Lower Masstrichtian); **3.** *Rotalipora cushmani* (Cenomanian); **4.** *Gavelinella vombensis* (Coniacian-Santonian); **5.** *Epistomina stellicostata* (Tithonian); **6.** *Dorothia kumni* (Hauterivian); **7.** *Lenticulina quenstedti* (Kimmeridgian); **8.** *Bolivinoides draco* (Masstrichtian); **9.** *Bolivinoides strigillatus* (Upper Santonian-Lower Campanian); **10.** *Pfendrina inflata* (Middle Jurassic); **11.** *Patellina subcretacea* (Albian); **12.** *Lenticulina kossmatina* (Middle Turonian); **13-14.** *Globotruncana gansseri* (Upper Campanian-Lower Maastrichtian); **15.** *Ammobacculities crespinae* (Lower Cretaceous); **16-17.** *Peckichara perlata* (Maastrichtian); **18.** *Verrneosis porites* (Triassic); **19.** *Beleminite* sp. (Upper Cretaceous); **20.** *Asteroidea* (Starfish) (Jurassic); **21.** *Cytherella disjuncta* (Upper Bathonian-Lower Callovian); **22.** *Procytheridea thopyensis* (Upper Bethonian-Lower Callovian); **23.** *Thalassinoides paradoxi* (Upper Cretaceous). (Courtesy: D.S.N. Raju and A. Govindan).

fishes were dominant. Amphibians, which came in during the Devonian, declined. Frogs appeared in Jurassic and salamanders in Cretaceous. Mammals were only nominally present.

Dinosaurs: It was Sir Richard Owen, who after examining the following three specimens, though already discovered earlier, coined the term *Dinosauria* (fearfully great lizard) in 1842.

Megalosaurus, "great lizard," named in print in 1822
Iguanodon – herbivorous beast – a few years later
Hyaeosaurus – woodland lizard – 1833

Almost 400 dinosaur species are now known from different parts of the world. They roamed around for about 165 Ma during this era. Three families of dinosaurs namely Titanosauridae, Abelisauridae and Nodosauridae have affinities with assemblage known from Madagascar (Malagasy), South America and southern Europe.

Dinosaurs appeared in the Late Triassic (about 230 Ma ago), evolved into some of the largest and most successful land animals of all time during the Jurassic and Cretaceous periods and then suddenly disappeared at the end of the Cretaceous (65 Ma ago).

Erect posture was the hallmark of early dinosaurs. Their sizes ranged from that of a whale to a chicken. They walked on their toes, raising the heel permanently from the ground. Some were bipedal and some quadrapedal. They are divided into two groups on the basis of the orientation of their hipbones: *Saurischia* and *Ornithischia* (Fig.8.7). In the *Saurischia*, the pubic bone is massive and points forward as in lizards. In the *Ornithischia*, the pubic bone is slim and has an extra branch that points backward as in birds. The *Saurischia* included gigantic herbivore sauropods, such as *Diplodocus* and *Camarasaurus*, as well as flesh-eating theropods such as *Tyrannosaurus* and *Velociraptor*. The *Ornithischia* included several groups of herbivores: the duck-billed ornithopods, the armoured *Stegosaurus* and *Ankylosaurus*, the horned ceratospians, and the thick-skulled *Pachycephalosaurus*. All ornithischians developed bird-like beaks for shearing leaves and branches. *Pterosaurus*, a flying reptile, closely related to dinosaur was of the largest creature ever to fly, filled the skies around the Earth. *Pterosaurus* was not a dinosaur as was believed earlier.

Based on microfloral study of Late Cretaceous faecal masses of herbivore dinosaur, it is inferred that the overall flora represent plants that grew in lowland in the vicinity of lake/water body having bloom of algae, fungi and sponges. Evidently such lowland areas with available water bodies surrounded

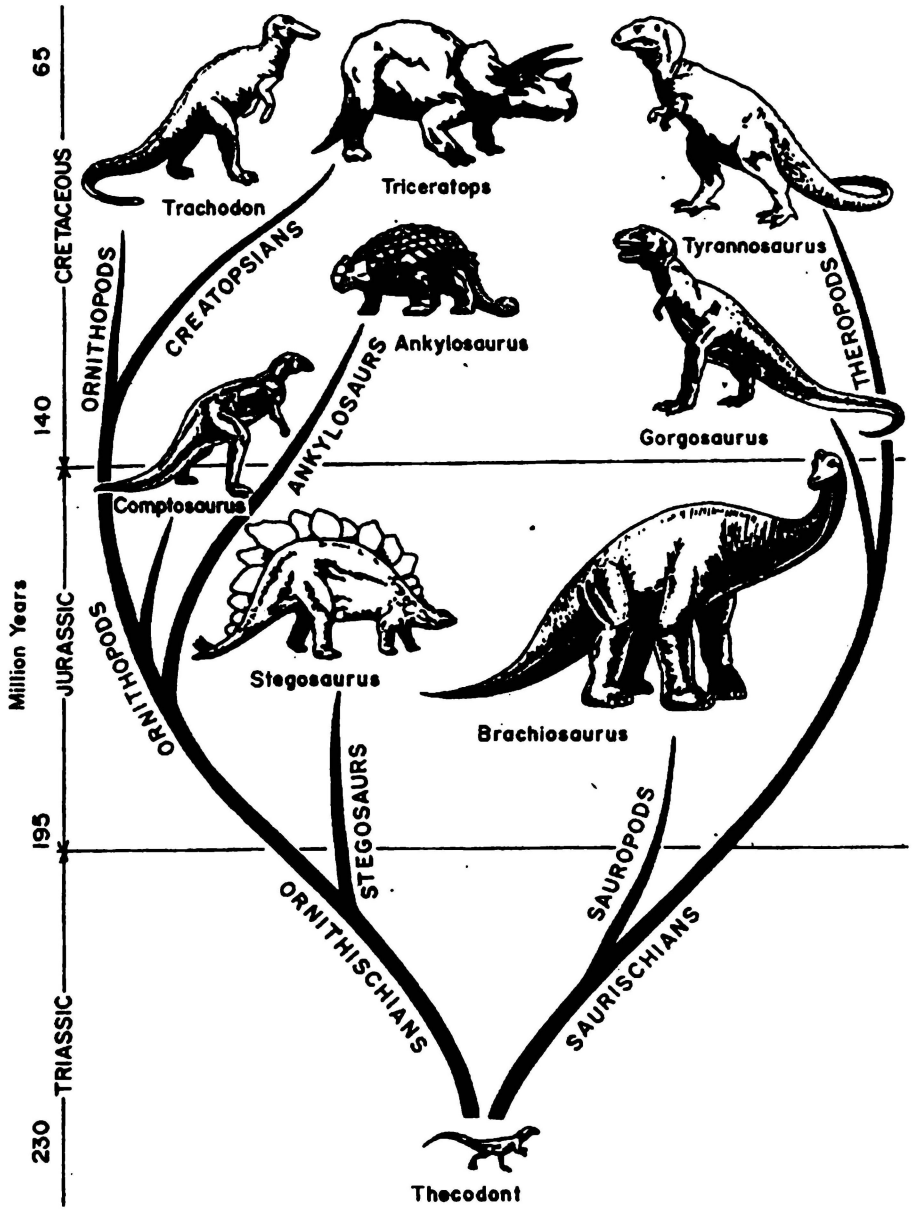


Fig.8.7. Stages in the evolution of important/major dinosaurs (Courtesy: P. Yadagiri).

by diversified flora were the preferred habitat of the herbivore dinosaurs in the terminal Cretaceous time in Peninsular India where semiarid climate prevailed with seasonal variation.

Dinosaur fossil localities are found mostly in western, central and southern India. A majority of the dinosaur fossils from India are from parts of Gujarat, western Madhya Pradesh, eastern Maharashtra and northwestern Andhra

Pradesh (Fig. 8.8). They are better known from Upper Cretaceous sediments (Lameta and equivalents) than from the older pre-Upper Cretaceous sediments or Gondwana Supergroup. Dinosaur eggs are so far unknown in the pre-Lameta dinosaur bearing sediments represented by Maleri (Carnian), Dharmaram (Norian to Rhaetian) and Kota (Liassic) Formations. Of these the Kota Formation has yielded near complete skeletons of *Barapasaurus tagoreii* (a prominent sauropod) and *Kotasaurus yamanapalliyensis* (a transitional prosauropod to early sauropod). The oldest dinosaur in India was found near the village of Nenmal in Adilabad district of Andhra Pradesh in Triassic rocks.

Palaeontologists have linked mass extinctions of the dinosaurs to terrestrial causes – geologic, climatic and ecologic. There was a proposal of a 26 Ma cycle of mass extinction episodes, during the last 250 Ma. Many hypotheses have been put forward to account for the extinction of these giant creatures from the surface of the earth, almost at the end of Mesozoic. For a long time it was presumed that during the end of Mesozoic there was a large scale volcanic

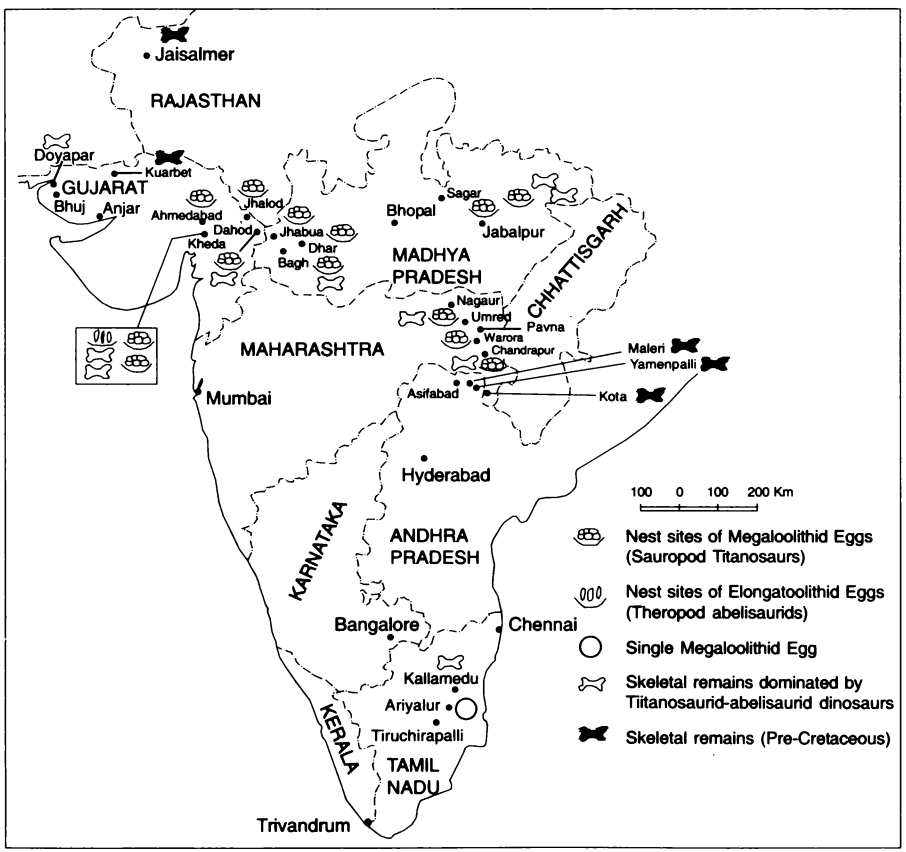


Fig.8.8. Map showing various dinosaur fossil localities in India (after Mohabey, 2001).

activity spewing out explosive material in many parts of the world and throwing out smoke and dust, which polluted the atmosphere, and that the dinosaurs could not stand the suffocation and perished. In India Decan volcanism at about 65 Ma was considered as responsible for dinosaur extinction.

In 1980, Luis Alvarez and his group discovered a thin layer of iridium-rich clay in many parts of the world, which coincided with the extinction event of the dinosaurs. Iridium is often found in the meteorites. A 10 km diameter giant meteorite is supposed to have caused a holocaust of unmatched dimension in the geologic history. The actual impact site is considered to be the Chicxubub in the Yucatan Peninsula in Mexico, though filled with thick pile of sediments. A second one, called Shiva Crater, about twice the size of Chicxubub, is reported off the west coast of India in the Arabian Sea. The fact that certain species of dinosaurs seem to have thrived even beyond the impact of these events casts doubts on this impact hypothesis. Deccan volcanism may have been only an accomplice, but not the main killer. While the heavy built forms were wiped out of existence, the relatively small-sized animals adopted themselves to a wide range of habitats in both land and sea, survived during the crisis and multiplied rapidly and diversified into a variety of forms during the Cenozoic.

Flora

Gymnosperms were already present in the Late Palaeozoic and angiosperms (flowering plants), ushered in the Jurassic, came in force during Cretaceous, the monocotyledons in Jurassic and dicotyledons in Cretaceous. Palynoforms present are used extensively in classification, correlation of strata and environmental analysis.

MAGMATIC ACTIVITY

The coming closer of the drifting India to the Asian continent had narrowed down the Tethys sea. Across the much narrowed sea, the strongly impacted southern margin of Tibet developed deep fissures. Through these welled up, in successive spurts, great volumes of granitic magma, giving rise to a belt of discordant intrusions of magma forming huge batholiths, stocks and bosses of granodiorite, granite and aplite. The granitic activity spread over a long period from 110-40 Ma, but the peak occurred about 60-45 Ma ago. It seems the intrusion of granite and granodiorite accompanied by eruption of lava in some places represented by Kohistan-Kailas-Gangdese-Lohit arc were related to the subduction of the floor of the Tethys sea beneath the continent of Asia.

TRIASSIC

It was Captain Strachey, who in 1851 discovered Triassic deposits in a number of localities in Niti Pass area in Garhwal, Kumaun. By about 1910, the biostratigraphy along with the zones was fairly well established. It was Carl Diener, who correlated the Triassic of India with that of other parts of the world. L.F. Spath carried out a revision of the fauna in the early 1930s and this process continued on till about 1960. It was Tozer's scheme that has been utilized by later workers in India in correlating Triassic formations. In India marine rocks of Alpine type developed along the Tethyan Himalaya belt in Kashmir, Spiti and Kumaun in the Triassic. The Triassic succession is more or less continuous in the Tethyan Himalaya including the passage from Permian. The Lilang Group in Spiti is considered the Indian type area for the Triassic. However, the maximum thickness is in Kashmir about 4000 m, which diminishes towards east being 1000 m in Spiti and 400 m in southeast Kumaun. Further in the Lower, Middle and Upper divisions in the Triassic of Spiti, they are conspicuously of unequal thickness 13, 140 and 1000 m, respectively. The classic section of the Triassic of Lilang (now also named Lulung), with supporting sections of Muth, Kaga and the Thanam river, lying in the Spiti region of Himachal Pradesh, have been the basis for most of the faunal zones, substages and stages in Himalaya and adjoining countries.

The Triassic sediments, originally deposited in the Tethys, are now exposed in Himalayan orogenic belt. These sediments were involved in complex folding, faulting, and thrusting during the Cenozoic.

Within a broad fossiliferous belt of Cambrian to Cretaceous strata from Kashmir to Bhutan, extending for more than 2000 km, are included the Triassic formations of Kashmir, Spiti, Nepal, Bhutan, Sikkim and the exotic blocks of Tibetan facies in Malla Johar.

Jammu and Kashmir

Lydekkar, Middlemiss, Bion and Wadia are among those who had made substantial contribution to our knowledge of the geology of parts of Jammu and Kashmir. The Triassic sequence in the central part of the Kashmir valley in Pastannah area in northern part of Tral valley (Fig.8.9), is as follows:

Lower Jurassic	Wumuh Fm.	Hettangian
Upper Triassic	Wuyan Fm.	Carnian-Norian
Middle Triassic	Khreuh Fm.	Anisian to Ladinian
Lower Triassic	Tindra Fm.	Spathian (~ Olenekian)
	Khunamuh Fm.	Greisbachian to Smithian (~Induan)

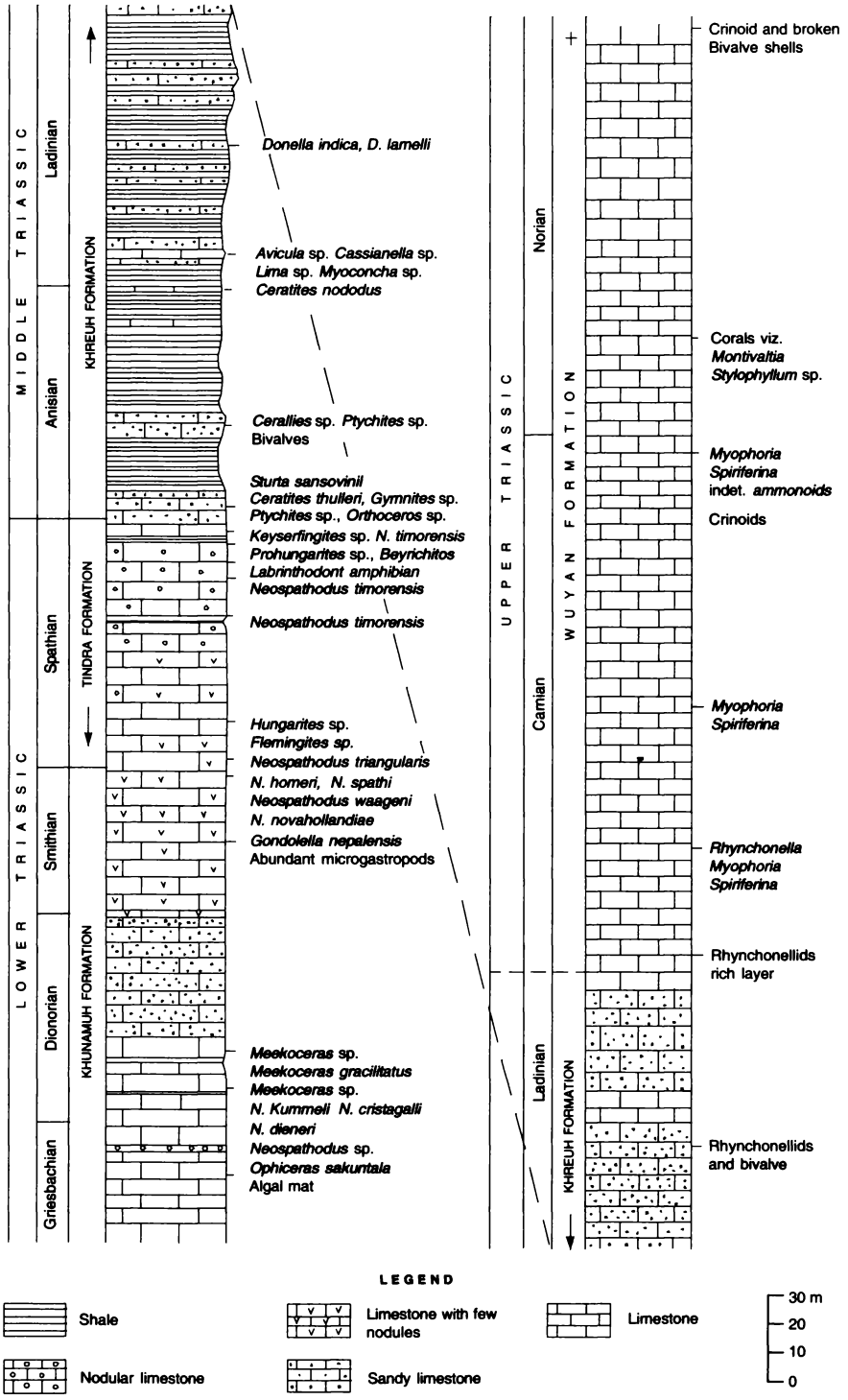


Fig.8.9. Triassic sequence, Tindara hillock, northwest of Pastannah, Tral valley, Kashmir (after Arora et al. 1996).

The boundary between Lower and Middle Triassic is just above the ammonoid *Keyserlingites* and conodont *Neospathodus timorensis* (*see* Fig.8.9). In the Upper Triassic occurs a persistent horizon with corals *Montlivaltia* and *Stylophyllum*, which is a marker horizon homotaxial with those in Spiti and Painkhanda areas. A sedimentary and faunal break occurs between the Wuyan Formation (Upper Triassic) and overlying Wumuh Formation (Lower Jurassic) in Sanger and Naubagh areas of Kashmir.

Jaw fragments of labyrinthodont amphibians were found from the Nodular Limestone (Middle Triassic) of Pastannah area in Kashmir. This indicates continuous presence of labyrinthodonts from Permian to Triassic in Kashmir region and their widespread distribution during the Triassic in India.

Lower Triassic: All the three ammonite zones of Lower Triassic, the *Otoceras, Ophiceras* and the *Meekoceras* are developed in the Vihi area of Kashmir. Though poorly exposed, the exposure at Nagburn consists of calcareous nodules overlying a thin band of black shales followed by 90 m-bedded blue limestone.

Middle Triassic: Lower Triassic Limestones are overlain by buff-coloured, thin-bedded limestones with thin intercalations of sandy limestone and shale with a 30 m thick grey thin-bedded limestone at the base, containing bivalves. These are overlain by nodular limestones and red and grey slaty limestone, rich in cephalopod fossils. These limestones are exposed in Pastannah, Khrew in Vihi and Batsuzi.

Upper Triassic: Upper Triassic limestones cover a much wider area, with a few thousand metres thickness, than the Lower and Middle units. Both *Megalodon* and *Halobia* Limestones of Upper Triassic of Spiti are represented in Kashmir. The Upper Triassic limestones are exposed in Anantanag district, east and west of Wular Lake, Tosh Maidan-Gulmargh-Golabgarh section, and Shams Abari area.

The exposures of Lower, Middle and Upper Triassic limestones are seen together in Pahalgam area and southeast of Wular Lake.

Jammu: Three isolated outcrops occur in association with the Zewan beds, in the Outer Panjal Trap belt, within the nummulitics in Poonch-Banihal area. These are composed of grey massive semi-crystalline limestone overlain by a crinoidal limestone with occasional fossil shells of bivalves. Besides the above, several Triassic outliers forming the core of Palaeozoic–Mesozoic synclines have been discovered in Bhadarwah-Chamba basin, Desa, Saribal Range and Warwan valleys of Doda district. These rocks are composed of fossiliferous

shale and shaly limestone in the lower part and platy and massive limestone with shale partings and sandstone intercalations in the upper part.

Ladakh: The main thickness of Triassic formation is seen in the Tibetan side of the Himalayan range. The broad belt of Triassic of Spiti continues through western Rupshu along the Tsarap Chu or Upper Zanskar Valley to the east of Kartse. These formations consist of limestone and dolomite of the upper division of the Triassic. Limestone rich in *Megalodon* is seen in the plains near Karakoram pass.

The entire sequence of carbonate rocks with subordinate quartz-arenite-argillite of the Triassic of Kashmir, that succeeds the Zewan Formation, is now designated as Sonamarg Group, after the famous tourist resort of Kashmir.

Eastern Karakoram: The Karakoram sedimentary belt comprises a thick sequence of Mesozoic rocks represented by Margo Formation, Burtsa Formation and Kazil Langa Formation (Fig.6.13). Margo Formation consists of grey, white and pink limestone and dolomite intercalated with grey to red shale and chert, with a thick horizon of brecciated limestone in the upper-middle part. The formation contains gastropods, cephalopods, corals, bryozoans, bivalves, crinoids and foraminifera. The upper part of the Margo Formation has yielded *Megalodon*, which assigns a Triassic age to it.

Himachal Pradesh

Spiti: The term Lilang was used by Hayden to denote Triassic rocks, which lie above the Kuling system (mainly Permian) and below the Kioto System (Rhaetian to Hettangian). Diener carried out detailed palaeontological examination of the fossil collections made earlier by Hayden and von Kraft. Based on faunal assemblage he presented a classification of Triassic of Spiti. The term Lilang Group was, however, introduced by Srikantia (1981) as a lithostratigraphic term for the entire sequence above the Kuling Formation and below the Spiti Formation incorporating Kioto Limestone into the Lilang Group. Based on extensive mapping in Spiti, the Lilang Group was divided into eight mappable formations by Bhargava (1987), necessitating creation of new names (Fig.8.10 and Table 8.1).

Lilang Group is dominantly a carbonate sequence of an enormous thickness and covers a wide area in Lahaul-Spiti-Kinnaur and Zanskar sectors forming part of the larger Spiti-Zanskar basin. With its spectacular Jura type of folds covering high ridges and valleys, the Lilang Group constitutes a conspicuous topography in the Higher Himalaya of Himachal Pradesh and Zanskar of Ladakh. In Spiti-Zanskar basin, the Lilang Group generally succeeds the Kuling Group

Table 8.1. Biostratigraphic classification of the Triassic System of Spiti (Hayden, 1904, 1908; Diener, 1912; Krishnan, 1982) and its comparison with lithostratigraphic classification (Bhargava, 1987) (source: Srikantia and Bhargava, 1998, opp. p.242)

System	Series	Stage	Name of beds		Description of beds	Thickness in metres	Group	Formation	Member
JURASSIC	Upper (Oxfordian) Spiti Shale				Black friable shale with *Belemnopsis gerardi*, *Mayaites*			SPITI	
	Lower Hettangian		Tagling Limestone	KIOTO LIMESTONE	Massive limestone and dolomite (with *Megalodontoids*, lamellibranch shells, also *Thecosmilia clathrata*, *Plesioptyxis*)	500		KIOTO	TAGLING
TRIASSIC	Upper Triassic	Rhaetian	Megalodon limestone (Para Stage)	KIOTO LIMESTONE	Massive limestone and dolomite (with *Spirigera noetlingi*, *Megalodon ladakhensis* and *Diceracardium himalayense* 100 to 135 m. above base)	250		KIOTO	PARA
		Norian	Quartzite Series		White and brown quartzites with grey limestones and black shlaes (with *Spirigera maniensis*)	100		NUNLUKA	
			Monotis shales		Sandy and shaly limestone with brown weathering shales and sandstones (with *Monotis salinaria* and *Spiriferian griesbachi*)	100		ALAROR	
			Coral limestone		Limestones (with *Spiriferina griesbachi*, and coral and crinoid remains) *Rhynchonella bambanagensis*	30		HANGRANG	
			Juvavites beds		Brown-weathering shales, limestones and sandstones (with *Juvavites angulatus*)	150		SANGLUNG	C
		Carnian	Tropites beds		Dolomite limestones (With *Dielasma Julicum*), Shales and dark limestones with ammonite bed (*Tropites subbullatus*) 130 m above base	100 200			B
			Grey beds		Grey shales and shaly limestone with bivalve bed 100 m above base, and an ammonite bed 16 m above base. (*Spiriferina shalshalensis* and *Joannites cymbiformis*)	150			A
			Halobia beds		Dark splintery limestone (with *Halobia* cf. *comata*). Bed with *Joannites thanamensis* near base	45			
	Middle Triassic	Ladinian	Daonella lime-stone		Hard dark limestone (with *Daonella indica*)	45		CHOMULE	
			Daonella shales		Black limestone, shaly limestone and shale (with *Daonella lammeli* and *Ptychites gerardi*)	50		KAGA	
		Anisian	Upper Muschelkalk		Concretionary limestone with shale bands (*Ptychites rugifer*)	6		MIKIN	
			Lower Muschelkalk		Dark shales and grey limestone (with *Keyserlingites dieneri*, *Sibirites prahlada*, *Spiriferina stracheyi*)	2			
			Nodular limestone		Hard nodular limestone with few fossils	20			
			Basal Muschelkalk		Shaly limestone (with *Rhynchonella griesbachi*)	1			
	Lower Triassic	Scythian	Hedenstroemia beds		Limestone with *Pseudomonotis himaica*. Shaly limestones and shales alternating (unfossiliferous) Thin-bedded limestones and shales (with *Hedenstroemia mojsisovicsi*, *Flemingites rohilla* and *Xenodiscus nivalis*)	182			
			Meekoceras zone		Thin-bedded limestones and shales with *Meekoceras varaha* and *Meekoceras lilangense*	1			
			Ophiceras zone		Grey limestone with *Ophiceras sakuntala* and *Pseudomonotis griesbachi*	.3			
			Otoceras zone		Brown limestone with *Otoceras woodwardi*; *O. clirei*	.6			
Permian			Productus shale		Dark shales with *Xenaspis* and *Cyclolobus* above and *Marginifera himalayensis* below	?	KULING	GUNGRI	

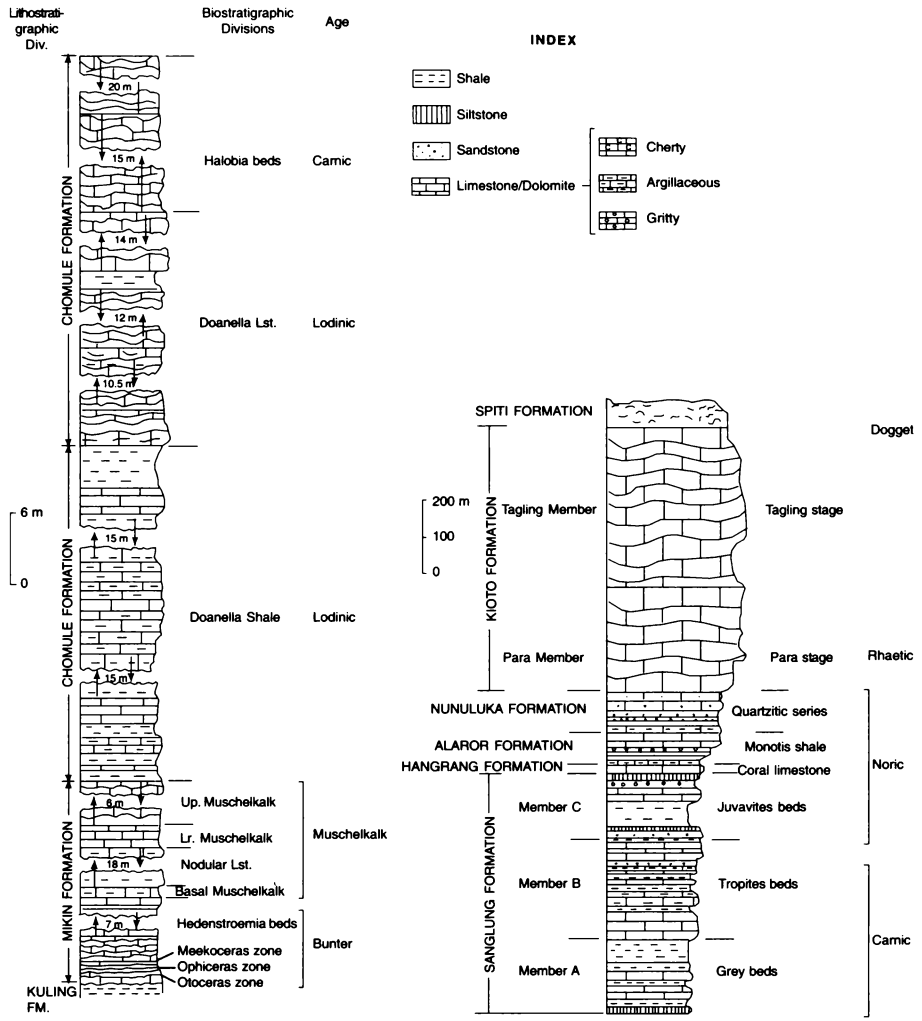


Fig.8.10. Lithocolumn of the Lilang Group showing lithostratigraphic subdivision against biostratigraphic subdivisions (after Bhargava, 1987, p.93) (reprinted with permission from Palaeontological Society of India).

along a conformable contact. It is, in turn, overlain by the Upper Jurassic Spiti Formation (Oxfordian), with a sharp contact.

Mikin Formation is well developed in Spiti and Kinnaur. In between the Gungri and Mikin Formations occurs a ferruginous bed apparently marking a hiatus during Dorashamian. The Mikin Formation is made up of dark grey-to-grey, locally cherty dolomite and shale lenses, repeated in cycles of carbonate shale units. The age of the formation ranges from Scythian to Anisian. The Kaga Formation consists of light to dark grey calcareous shale, locally thin lenticular beds of limestone and dolomite, weathering to earthy yellow colour.

Shale with abundant thin-shelled pelagic *Daonella,* and carbonate with filamentous pack/wackestone indicate neritic to sub-tidal environment for the formation. The microfacies, bedding features, abundant pelagic forms like *Daonella* and *Halobia* and layers locally rich in radiolarian, indicate an environment of sedimentation between open sea shelf and basin margin, for the Chomule Formation. The folded Sanglung Formation is well exposed at Rangrik.

The Hangrang Formation (reefs) is exposed in Hangrang Pass, Tapuk (Kinnaur), Giu *nala,* Chidang, Pin-Parahio confluence and Rangring. The succeeding Alaror Formation is well exposed along the Atargoo-Guling road, about one kilometre upstream of the Pin-Spiti confluence. The lithology and microfacies of the Nunuluka Formation suggest deposition varying from mud/ tidal flat to coastal area. The Kioto Formation was earlier described as Megalodon Limestone, but later named as Kioto Limestone. The microfacies of the rock units of the Para Member are characteristic of winnowed shelf edge sand area with tidal channels. It has been considered to be a transgressive facies. The Tagling Member is well exposed near Sakti, Giumal and Kibber. Microfacies and low-density fauna suggest depositional environment of winnowed shelf edge to restricted platform. The glauconitised oovoids and foraminiferal tests symbolise hard ground indicating deepening of the shelf. The top of the Tagling Member thus has been regarded to signify a submarine hiatus. Recently a revision has been made of the litho-stratigraphy of the Lilang Group, which is now raised to a Supergroup. The alternative litho-stratigraphic nomenclature is given in Fig.8.10A.

Southwest Lahaul: In the Tandi belt, described earlier, the Tandi Group is divisible into Kukti, Gushal and Dilburi Formations. The Gushal Formation consists of white and dark grey, pink-bedded limestone with interbeds of greyish blue dolomite. The formation has yielded *Japonites sugriva, Ptychites* aff. *everesti, Koninckites* cf. *yudihisthiara* of Muschelkalk affinity, besides *Spirifer* sp., *Rhynchonella* sp., foraminiferids, corals, echinoid spines etc. indicating a Triassic age.

Chamba basin: Here the Kalhel Formation overlies the Salooni Formation of Permian age and comprises limestone and dolomite with interbedded quartzite in the upper part. Limestone contains ossicles of crinoids in the lower part. A teleostean fish *Saurichthys* has been reported from the topmost bed of Kalhel Formation. The formation is considered to be of Triassic in age. Both the Salooni and Kalhal are considered to represent the major Permo-Triassic marine transgressive event in the Himalaya, which is common to Bhadarwah area of Jammu and the Tandi belt of southwest

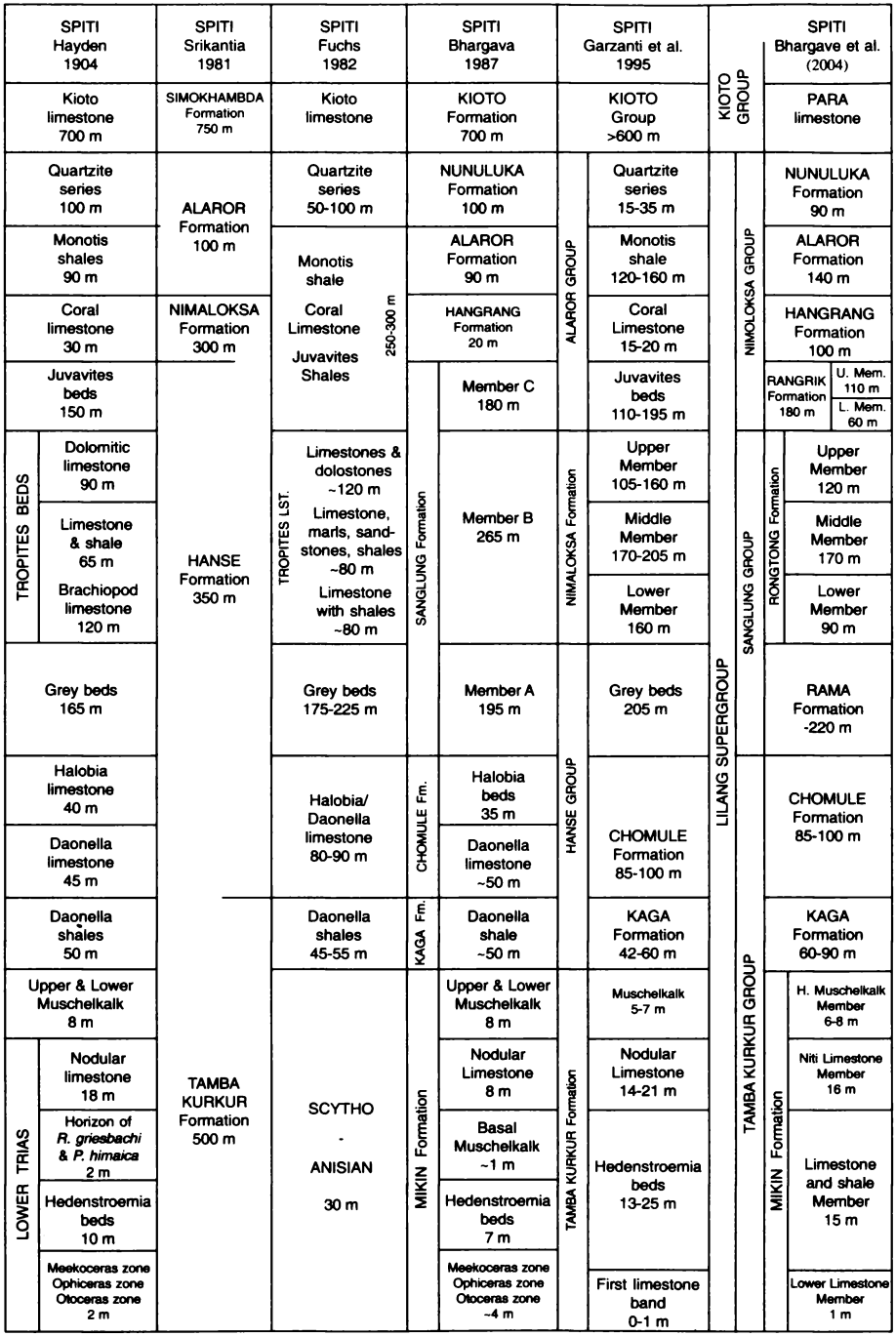


Fig.8.10A. Summary of alternative lithostratigraphic nomenclature for the Triassic of Spiti (Bhargava et al. 2004).

Lahaul. The Chamba basin is actually the extension of the Bhadarwah basin and these two together constitute a larger Permo-Trias basin in the northwest Himalaya.

Uttarakhand

Painkhanda (Kumaun-Garhwal): Sections of Triassic are exposed in the Bambanag and Shal Shal cliffs in northwestern part of Kumaun. The Painkhanda section, though similar to that of Spiti, has some variations. The Ladinic stage dwindles down to an insignificant 28 m and the Upper Trias is also much less thick. Table 8.2 presents the stratigraphic divisions, the lithology, invertebrate fauna, characteristic spore-pollen taxa and standard stratigraphic equivalents. The Kuling Formation of Upper Permian underlies the Shal Shal Formation.

Byans: Triassic is also developed in Byans in northeastern Kumaun and also in northern Kumaun, near the border with Tibet. In the latter region, however, it has been divided into (i) Chocolate Series, (ii) Kalapani Limestone, (iii) Kuti Shales and (iv) Kioto Limestone.

Triassic palynoflora have been recovered from Rambakot and Rimkhim Members of the Shal Shal Formation. The assemblage compares closely with that of the Lower Panchet Formation of Lower Gondwana, as well as other equivalent beds from Peninsular India. The Panchet Formation could be dated as Induan Stage, the lowest unit of Triassic.

Malla Johar: Rootless klippen floating in a sea of serpentinite, popularly known as the "exotic blocks" of Malla Johar of Tibetan Facies, are the isolated blocks scattered over volcanics in the areas of Chitchun and Keogarh in the north and northeastern parts of Uttaranchal. These are blocks of white to pinkish limestone. Exotic blocks of Malla Johar contain Permian, Triassic or Jurassic fossils belonging to different provenances. They have been classified into (i) Exotic blocks in the flysch, (ii) Exotic blocks in the basic volcanics and (iii) the Kiogarh exotic mass. Many ammonite species were recorded from these blocks. Blocks with *Koninckites* and *Durgaites* fauna of Upper Carnian are well known. The Carnian fauna is allied to the Mediterranean zoogeographic province. It is obvious that these blocks belonged to parts of thrust sheets (Fig.8.11). The basal part of the limestone, though unfossiliferous, is succeeded by red marl and limestone yielding Tithonian (Upper Jurassic) *Calpionella*, and the grey well-bedded dense limestone is rich in micro-fossils (radiolarian and sponge spicules), all attributable to Cretaceous age.

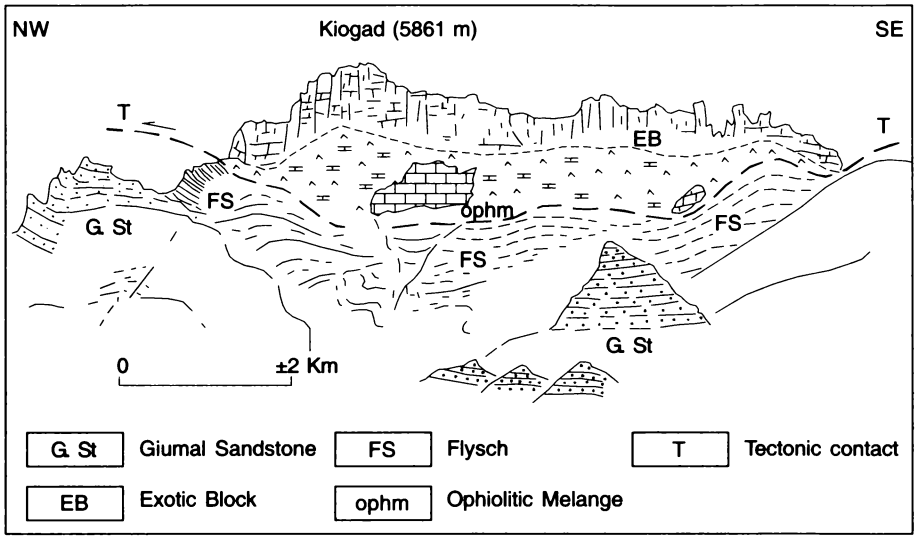


Fig.8.11. Exotic blocks of the Malla Johar Kiogad 1 Peak at the Indo-Tibet border, north of the State of Uttarakhand (after Sinha, 1989, p.68). (© 1989 John Wiley and Sons Limited. Reproduced with permission).

Nepal

Triassic rocks occur in Tinkar Lipur area, Takkola in Central Nepal. The ammonite faunas include *Halorites, Anatomites, Thisbites, Sirenites, Gymnites, Arcestes, Pinacoceras* and many others besides *Halobia*. They indicate Carnic and Noric age.

Sikkim

In the Lachi ridge, the calcareous sandstones of Chho Lhamo (Tso Lhamo) series, containing Upper Permian fossils, are overlain by several hundred metres of quartzites and shales, which may be of Triassic age. The few fauna they contain suggest Anisian age (lower Middle Triassic).

Bhutan

About 2000 m thick Linghshi Series contains *Orthoceras, Daonella, Lima* and *Pseudomonotis*.

Rajasthan

There is no record of Triassic sediments in Rajasthan. However, Bhuana Formation of Triassic has been reported from subsurface in Jaisalmer basin (Fig.8.14).

Table 8.2. Permian-Jurassic formations of Painkhand (Niti area) (after Tiwari et al. 1996)

Era	System	Formation	Member	Lithology	Fauna	Age	Characteristic spore-pollen taxa
Mesozoic	Jurassic	Kiogad Formation	Spiti Member (295 m)	Grey to black shales with calcareous nodules and rich in ammonites	*Blanfordiceras* Assemblage	Late Upper Tithonian	*Cyathidites*, *Cooksonites*, *Klukisporites*, *Contignisporites*, *Cicatricosisporites*,
					Himalayites *Corongocera* *Aulacosphinctes* Assemblage	Early Upper Tithonian	*Kraeuselisporites*, *Podocarpidites*
					Hildoglochiceras *Virgatisphinctes* Assemblage	Mid Tithonian	*Callialasporites*, *Araucariacties*, *Laricoidites*
					Torquatisphinctes- *Aulacosphinctoides* Assemblage	Lower Tithonian	
			Chhojan Member (3.5 m)	Oolitic ferruginous arenaceous limestone with *Belemnites*	*Belemnites gerardi* (no ammonoids)	Oxfordian Kimmeridgian	
			Lapthal Member (60 m)	Thinly bedded limestone full of Lumachelle	Indeterminate shell fragments, ferruginous oolite at base with *Macrocephalites*, *Dolikocephalites*	Callovian	*Densoisporites*, *Cyathidites*, *Dubrajisporites*, *Callialasporites*, *Araucariacites*, *Infernopollenites*, *Staurosaccites*, *Podocarpidites*

Table 8.2. Contd...

Era	System	Formation	Member	Lithology	Fauna	Age	Characteristic spore-pollen taxa
	Triassic	Shal Shal Formation	Kioto Member (500 m)	Limestone, arenaceous limestone and quartzites with rare fossils including *Megalodon*	*Anodontophora griesbachi*, *Spiriferina greisbachi*, *Halorites procyon*, *Proclydonautilus greisbachi*	Norian	Poor yield, highly degraded specimens, rarely identifiable
			Rimkhim Member (80 m)	Alternation of limestone and shale with ammonites	*Halobia* cf. *comata*, *Traumatocrinus*, *Daonella indica*, *Spirigera hunica*	Carnian	*Densoisporites*, *Lundbladispora*, *Kraeuselisporites*, *Playfordiaspora*, *Satsangisaccites*, *Brachysaccus*, *Minutosaccus*, *Podocarpidites*
			Hoti Member (28 m)	Dominantly limestone and shale alternation rich in ammonites	*Ptychites rugifer* *Spiriferina stracheyi*, *Keyserlingites dieneri*	Ladinian	
			Niti Member (30 m)	Massive nodular limestone	*Rhynchonella griesbachi*, *Sibirites prahlada*	Anisian	
			Rambakot Member (10 m)	Alternation of limestone and shale with *Otoceras* and *Ophiceras* assemblage	*Flemingites rohilla*, *Pseudomonotis himaica*, *Meekoceras varaha*, *M. markhami*, *Otoceras woodwardi*, *Ophiceras tibeticum*, *Episageceras dalailamiae*, *Ptychites scheibleri*, *Ophiceras sakuntala*	Scythian	*Lundbladipora*, *Densoisporites*, *Playfordiaspora*, *Crescentipollenites*, *Alisporites*, *Klausipollenites*, *Satsangisaccites*, *Lunatisporites*, *Goubinispora*
Palaeozoic	Upper Permian	Kuling Formation (140 m)		Black shale with nodules and fine grained sandstone at the base. In the middle limestone lenses contain *Spiriferella rajah* & *Paramarginifera himalayensis*	*Paramarginifera himalayensis*, *Spiriferella rajah*, *Cyrtella nitiensis*, *Brachythyrina* sp.	Late Permian	*Densipollenites*, *Crescentipollenites*, *Striatopodocarpites*, *Satsangisaccites*, *Klausipollenites*, *Lunatisporites*

Kutch

Non-marine rocks with palynoflora of uppermost Triassic (Rhaetic) have been recognised in the subsurface in Banni by ONGC. The horizon was located at a depth of about 1700 m below the surface.

Fauna and Flora

Triassic marine life comprised ceratitic and ammonitic ammonoids, terebratulid and rhynchonellid brachiopods, first Nautilus, first dibranchiates, scleractian corals, more evolved ostracodes, acritarchs, conodonts, bivalves, gastropods, crinoids, echinoids etc.

First record of conodonts from India was made from the Pastannah hill (Kashmir) around 1966. These were prolific in Triassic times. Some of the species are confined to certain sections of Triassic in different parts of NW Himalaya. A few of the important fossils in the above region are listed below in the order of progressively younger appearance:

Lower Triassic:	*Neospathodus timorensis*
(Spiti)	*Neogondolella carinata*
Middle Triassic:	*Neogondolella constricta*
(Kiogarh Valley)	*N. mombergenesis*
	N. navicula navicula
Upper Triassic: (Kashmir,	*Xaniognathus newpassensis*
Ladakh, Spiti)	*Metapolygnathus polygnathisformis*
Rhaetic: Niti Pass;	Youngest conodont species from India.
Painkhanda (Kumaun):	*Neospathodus lanceolatus*

Besides the conodonts, coral reefs are also common. Reefs of Middle Norian age are reported from Rangring, the Pin-Spiti confluence, Kiomo, Latarse (all Spiti) and Pamachen, Hangrang Pass and Tapuk (Kinnaur). All the reefs are rather small (up to 30 m thick) and form a low angle contact with the underlying beds. Main reef builders are calcisponges, corals, tabulozoans and hydrozoans. The composition and distribution of the Spiti-Kinnaur reefs are comparable to a rimmed carbonate platform.

Among the plants, thalo-, bryo-, artho- and pteridophytes were the most common though cycads and conifers were also present. Palaeobotanical evidence indicates a four-fold increase in atmospheric carbon-di-oxide concentration and suggests an associated 3 to 5° "green house" warming across the boundary, which perhaps was partially the cause for the extinction of many

species. The end Triassic mass extinction event (205.7±4 Ma ago) was the third largest in the Phanerozoic, resulting in the loss of over 30% of marine biota, 50% of tetrapod species, >95% turnover of mega floral species and marked micro-floral turnover in Europe and North America.

In terms of absolute ages, the Triassic which extends from about 250 to 205 Ma with an approximate duration of 45 Ma, is further split on the basis of rapidly evolving guide fossils – the ammonoids, into 7 standard stages, 14 sub-stages, about 25 zones and 55 sub-zones. The average duration of a sub-zone is one million years or less representing the stratigraphic range of one species.

Permo-Triassic Boundary

The boundary delineation by faunal criterion depends on the development and availability of a continuous marine section, where the biological events established in relation to the boundary can be examined and traced.

Global Boundary Stratotype Point (GBSP) of Permian/Triassic (P/T) boundary is placed at the first occurrence of conodont species *Hindeodus parvus,* in the evolutionary lineage *latidentatus-parvus-turgida-isarcia,* which is transitional between *Hindeodus* and *Isarcicella.* The radiometric dating of the horizon corresponds to 251 Ma.

There has been a strong suggestion that the level of first occurrence of the distinctive conodont species *Isarcicella isarcia (Huckrieda)* (in which are included conodonts variously described as *Anchignathodus parvus*, *Hindeodus parvus* and *Isarcicella? parvus),* can be recognised stratigraphically at equivalent levels in Kashmir, south China, Iran, Italy, and western United States. The base of the Isarcia zone corresponds closely to the base of the Werfen Formation of the Alps and to the top (not the base) of the *Otoceras woodwardi* zone, as it developed in Kashmir.

The Guryul ravine section in Kashmir, was submitted and discussed in detail for the specific purpose of delineating this boundary. It has not, however, yet been officially accepted as such by the International Stratigraphic Commission. Though in Kashmir there are several sections, where continuous development of Permian and Triassic strata can be studied, like at Pahalgam, Pir Panjal, Bhallesh etc., all of them have some demerits. The Guryul ravine section has easy accessibility, besides containing major part of Permian and Triassic, even up to Jurassic, and being least disturbed.

The Guryul succession consists of an arenaceous sequence grading upward through the argillaceous rocks into a carbonate sequence. The lower part of the transitional facies of argillaceous rocks (black shales) has yielded a mixed faunal assemblage comprising productids of Permian age in association with the Lower Triassic bivalve *Claria.* Permian Productids have survived into the

earlier Triassic and the boundary is suggested at the base of the black shales. Conodontists have favoured the boundary above *Otoceras woodwardi* zone, while ammonite specialists have stuck to the traditional base of *O. woodwardi* zone.

The base of the *Otoceras* zone is apparently the level at which a maximum change in biota is recorded and it is traceable throughout the Himalaya. Overall the Guryul ravine section in Kashmir, with support from the Pahalgam section, is considered to be the best reference section for the transition beds. However it lacks Dorashamian fossils (uppermost Permian-Changhsingian), but has an excellent development of Lower Triassic strata. Across the P/T boundary palynomorphs show an evolutionary shift and not a mass extinction.

The P/T boundary for the continental sediments is established for the first time in the Banpetalic *nala* section of the Gondwana basin of Raniganj (West Bengal), based on the occurrence of estheriids, a group of very small crustaceans. Three estheriid horizons have been identified in the Panchet Formation of Raniganj. The Geological Survey of India has proposed the *nala* section as the first continental stratotype for the P/T boundary.

JURASSIC

In India, marine Jurassic rocks are distributed along the Tethyan belt from Ladakh-Zanskar-Kashmir through Spiti to Malla-Johar (Fig.8.2), and in Kutch and Jaisalmer (Western India). Doubtful uppermost Jurassic sediments are present along the East Indian coast between Chennai (Madras) and Kanyakumari (Cape Comorin) and in the exotic blocks in Himalaya.

Rich and diverse marine life was present during the Jurassic. The rate of change in the organic world was relatively faster and more pronounced than anytime earlier. Among the invertebrates the groups present are the molluscs (cephalopods, bivalves and gastropods), brachiopods (rhynchonellids and terebratulids), corals (hexa), bryozoa, crinoids, echinoids, foraminifers, ostracodes, acritarchs, coccoliths, radiolarians and dinoflagellates. The vertebrates are crocodiles, reptiles, primitive mammals, archaeopteryx and fish. The plants are the cycads, conifers, and fern, besides the palynoforms.

Among marine life, a major extinction took place at the end of Triassic. However, in nonmarine life, neither megafossils nor palynofossils showed significant change across the Triassic/Jurassic boundary. This situation is similar to that of P/T boundary, where palynomorphs show an evolutionary shift and not a mass extinction. The base of the Jurassic and of the Hettangian Stage is indicated by *Psiloceras planorbis* zone (or simply *planorbis* zone; gastropod). The Triassic–Jurassic passage in Himalaya shows lithological continuity.

In terms of absolute ages, the Jurassic extends from about 205 to 145 Ma with an approximate duration of about 60 Ma. It is informally divided into three series (lower, middle and upper) and in turn into a total of 11 stages (4+4+3). In total there are about 65 ammonoid zones (chronozones) and about double the number of sub-zones. The zones, although conventionally named after some prominent ammonoid species, are mostly indicated by the assemblages present in that zone.

Kutch (Kachchh)

Stratigraphy: Table 8.3 represents Mesozoic stratigraphy of Kutch with major chrono-stratigraphic units along with important fossils, whereas Table 8.3a represents the lithostratigraphy of Kutch from Bathonian (Jurassic) to Albian (Cretaceous). Recent studies of ammonite fauna in particular in some parts of Kutch have enabled to arrive at a very detailed bio-chronostratigraphic division of the Middle Jurassic formations between Bajocian and Callovian (Fig. 8.12). Based on detailed mapping and lithofacies studies of the intra-rift subbasins, Biswas (1991) evolved a lithostratigraphic classification. Three lithostratigraphic domains were identified – Kutch Mainland, Pachham and Eastern Kutch. Inter domain correlation was done by tracing the marker beds (Table 8.3a; folder). The lithostratigraphic boundaries are on the basis of major lithologic breaks, unconformities and change over from one environment to another. In a highly fossiliferous and lithologically differentiated stratigraphic sequence as in Kutch there is adequate scope for sub-dividing it in all the three categories – litho-, bio-, and chronostratigraphy.

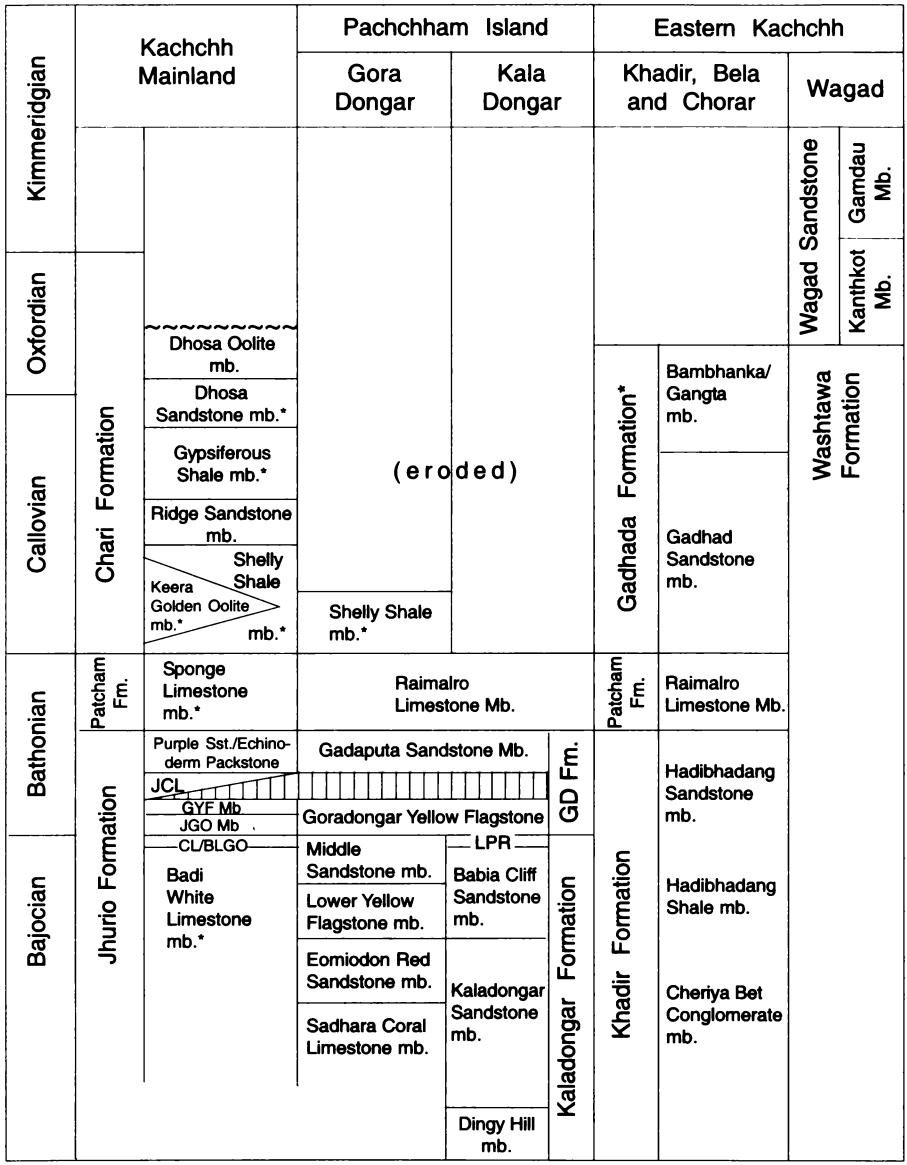
Structure: The western margin of the Indian Peninsular Shield is affected by rifting along major Proterozoic orogenic trends viz., Aravalli-Delhi and Satpura mobile belts. Kutch rift is the northernmost pericontinental embayed basin situated between the subsurface Nagar Parkar Uplift (NPU) in the north, Radhanpur-Barmer arch in the east and Kathiawar Uplift in the south (Fig.8.13). The two uplifts are the rift shoulders respectively along Nagar Parkar Fault (NPF) and North Kathiawar Fault (NKF) and the Radhanpur-Barmer arch is the hinterland. This arch is the western shoulder of the Cambay rift, which terminates the west to east Kutch rift. Besides horsts (H), grabens (G) and half-grabens (HG), there are anticlines and domes of varying sizes and shapes. The Kutch basin evolved in two stages: (i) Rift stage: basin subsidence along normal faults and (ii) Inversion stage: uplifts along the same faults by reverse movements. The east-west oriented, fault-bounded, ridges and depressions influenced the thickness and facies distribution of the formations here. The westerly plunge of the basin is reflected in the general westward thickening of

Table 8.3. Mesozoic stratigraphy of Kachchh (source: Merh, 1995, pp.136-137)

Age		Sub-divisions		Leading fossils
CRETACEOUS	UMIA (1000 m)	Post-Aptian	Bhuj beds (Umia Plant beds) Sandstones and shales	*Palmoxylan* in upper beds *Ptylophyllum* flora, similar to Jabalpur flora in lower beds
		Aptian	Ukra beds-Marine calcareous shales	*Australiceras, Colombiceras Cheloniceras, Topaeum* etc.
		U. Neocomian	Umia beds Barren sandstones and shales	Unfossiliferous
		Valanginian	Trigonia beds. Barren sandstones	*Trigonia* Unfossiliferous
		U. Tithonian	Umia ammonite bed	*Virgatosphinctes, Micracanthoceras, Ptychophylloceras, Hemilytoceras, Umiatites*, etc.
JURASSIC	KATROL (300 m)	M. Tithonian	Up. Katrol shales	*Hildoqlochiceras, Dorsoplanites Haploceras*
		M. Tithonian	Gajansar beds	*Belemnopsis, Streblites, Phyloceras, Hildoglochiceras*
		L. Tithonian	Upper Katrol (barren) sandstone	*Aulacosphinctoides, Virgatosphinctes*
		M. Kimmeridgian	Middle Katrol (red sandstones)	*Waagenia, Katroliceras, Panchysphinctes, Aspidoceras*
		M. Kimmeridgian	Lower Katrol (sandstones, shales marls)	*Torquatisphinctes, Aspidoceras, Ptychophylloceras, Taramelliceras, Streblites, Waagenia, Hybnoticeras*
		U. Oxfordian	Kanthkot sandstone (Bimammantum zone)	*Epimayaites, Prograyiceras, Ataxioceras, Biplices, Prosophinctes Torquantisphinctes, Trigonia*
	CHARI (360 m)	Upper to Lower Oxfordian	Dhosa oolite (green and brown oolites) (Transversarium zone)	*Tramelliceras, Discosphinctes Perisphinctes, Mayaites, Epimayaites, Paracenoceras, Peltoceratoides*
		U. Callovian	Athleta beds (marls and gypseous shales)	*Peltoceras, Orionoides*
		M. Callovian	Anceps beds (marls and gypseous shales)	*Perisphincites, Indosphinctes, Reineckeia, Kinkeliniceras, Hubertoceras*
		M. Callovian	Rehmanni beds (yellow limestone)	*Reineckeia, Sivajiceras, Idiocycloceras, Kellawaysites*
		M. Callovian	Macrocephalus beds (shales with calcareous bands, with golden oolite-diadematus zone in the upper part	*Macrocephalites, Dolichocephalites Indocephalites, Kamptocephalites, Pleurocephalites, Belemnites*
	PACHCHAM (300 m)	L. Callovian	Pachcham coral bed	*Macrocephalites, Sivajiceras, Procerites, Thamnastrea, Stylina, Montlivaltia*
		L. Callovian to Bathonian	Pachcham shell limestone	*Macrocephalites, Trigonia, Corbula*
			Pachcham basal beds (Kuar Bet Beds)	*Corbula, Eomiodon, Trigonia*, etc.

Table 8.3a. Lithostratigraphy of Kutch (Biswas, 1991, p.79)

AGE	MAIN LAND			PACHHAM ISLAND			E. KUTCH (KHADIR - BELA - WAGAD)		
	FORMATION	MEMBER	LITHOLOGY	FORMATION	MEMBER	LITHOLOGY	FORMATION	MEMBER	LITHOLOGY
NEOCOMIAN - ALBIAN	BHUJ 815 m	UPPER 230 m +	Cross bedded sandstone with kaolinitic claystone beds and sandy ironstone bands						
		UKRA 30 m	Developed only in west Glauconitic sandstone and shales, fossiliferous						
		GHUNERI (w) or LOWER (E) 525 m	Rhythmic sequence of sandstone-shale-ironstone bands. Abundant plant fossils						
			Unconformity						
	JHURAN 760 m	KATESAR 180 m	Cross-bedded sandstone with calc bands, locally fossiliferous, developed in west only						
KIMMERIDGIAN TO TITHONIAN		UPPER 300 m	Thinly bedded sandstones calcareous; fossiliferous						
		MIDDLE 160 m	Mainly shales, fossiliferous						
		LOWER 120 m	Shale/Sandstone alternation, fossiliferous						
			Disconformity						
OXFORDIAN	JUMARA 275 m	DHOSA OOLITE 115 m	Shales with oolitic limestone bands fossiliferous						
			Diastem						
CALLOVIAN		MIDDLE 75 m	Sandstone in the east. Limestone with golden oolite in the west						
		LOWER 85 m	Olive green shales fossiliferous	GORADONGAR 154 m	Modar Hill 130 m +	Upper sandstone Lower shales			
					Raimalro 8 m	Limestones, cherty			
					Gadaputa 6 m	Sandstones			
					Flagstone 6 m	Flaggy limestones with golden oolite			
BATHONIAN	JHURIO 290 m	UPPER 70 m	Bedded limestone	KALA-DONGAR 470 m	Kaladongar sandstone 180 m	Cross-bedded sandstones			
		MIDDLE 85 m	Shale interbedded with golden oolitic limestone		Kuarbet 290 m	Interbedded shale and sandstones			
		LOWER 135 m	Interbedded limestone / shales						
							WAGAD SANDSTONE 365 m	Gamdau 165 m +	Rhythmic sequence of feldspar, sandstones - shales - red ironstone bands. Occasional plant fossils
								Kanthkot 200 m	Upper : Sandstone / shale alternation with fossil bands Middle : Massive cross-bedded sandstones Lower : Silty fossiliferous shales (?) Paraconformity
							KHADIR (KHADIR ISLAND) 650 m	WASHTAWA (WAGAD) Bambhanka shales 160 m	Mainly shales fossiliferous
								Gadhada 185 m	Shales and sandstones
								Hadibhadano 260 m	Upper part : Limestone top cherty Middle part : Sandstones Lower part : Shales, fossil.
								Cheriyabet 25 m	Petromict granite - Cobble - conglomerate and arkose
							PRECAMBRIAN		GRANITIC BASEMENT



JCL - Jumara Coral Limestone mb*; GYF - Goradongar Yellow Flagstone Mb.; JGO - Jhura Golden Oolite mb*; CL/BLGO - Canyan Limestone/Badi Lower Golden Oolite; LPR - Leptosphinctes Pebbly Rudstone.

Fig.8.12. Lithostratigraphic framework of Middle Jurassic and lower Upper Jurassic rocks of the Kachchh Basin. The lithostratigraphic terms are partly those of Biswas (1980), partly they are the traditional terms introduced by Waagen (1875). Yet other terms (marked with an asterisk) are new and await formal description (after Fürich et al. 2001). (Reprinted with permission from Palaeontological Society of India).

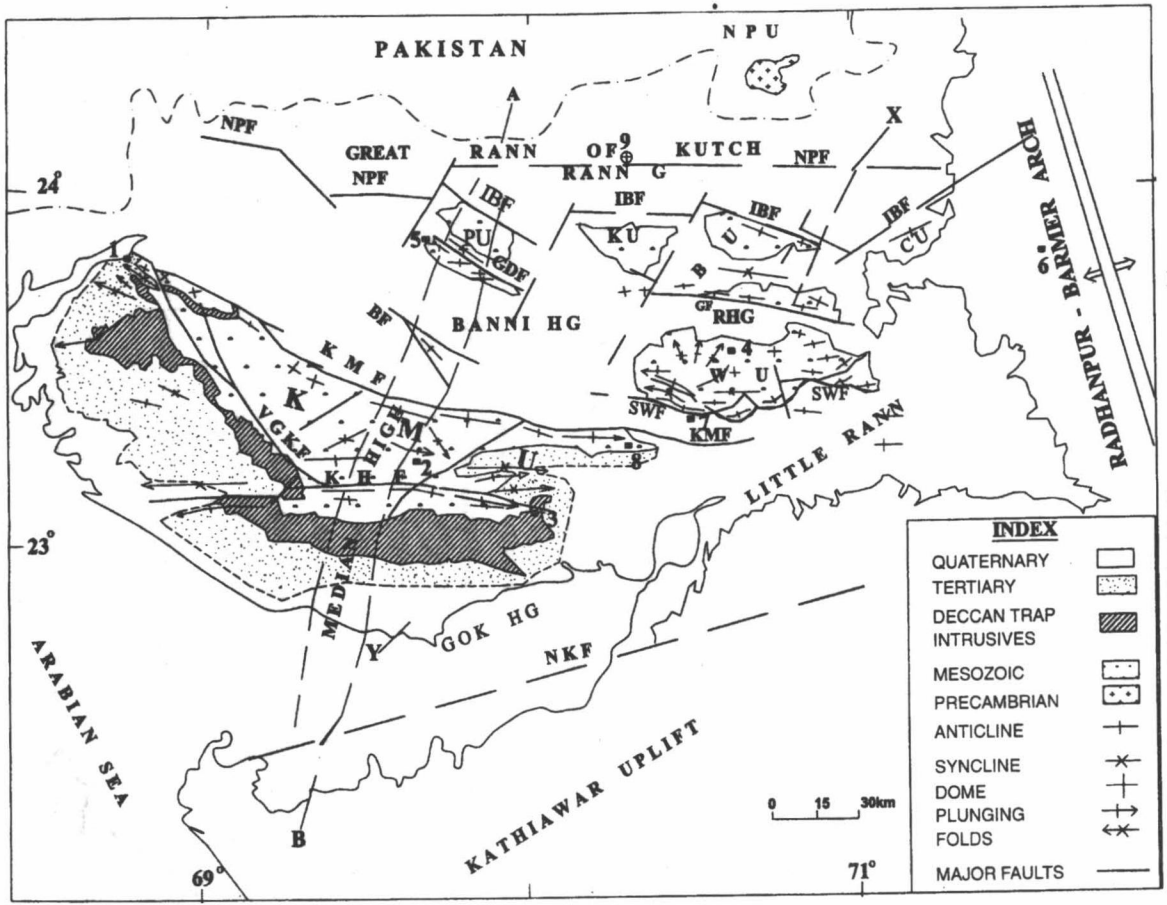


Fig.8.13. Tectonic map of Kutch (modified after Biswas, 1981). **1**. Lakhpat, **2**. Bhuj, **3**. Anjar, **4**. Rapar, **5**. Khavda, **6**. Radhanpur, **7**. Adhoi, **8**. Bhachau, **9**. Meruda Takkar (after Biswas and Khattri, 2002).

NKF - North Kathiawar Fault; **NPU** - Nagar Parkar Uplift; **NPF** - Nagar Parkar Fault; **IBF** - Island Belt Fault; **PU** - Pacham Uplift; **GDF** - Goradongar Fault; **KU** - Kadir Uplift; **BU** - Bela Uplift; **GF** - Gedi Fault; **RHG** - Rapar Half Graben; **WU** - Wagar Uplift; **VGKF** - Vigodi-Khirasra-Gugriana Fault; **KHF** - Katrol Hill Fault; **CU** - Chorar Fault; **SWF** - South Wagad Fault; **KMF** - Kutch Mainland Fault; **IBU** - Island Belt Uplift; **KMU** - Kutch Mainland Uplift; **GOK HG** - Gulf of Kutch Half Graben; **HG** - Half Graben; **WU** - Wagad Uplift.

the sedimentary units deposited during the two Mesozoic transgressive and regressive cycles, and their relatively deeper-shelf facies prograding towards west. Based on these, it can be very well seen that the lithological horizons with all their variations in facies must have presented a complicated picture to unravel accurately the stratigraphic sequence in this basin. It is no wonder that differences of opinion exist when correlation is attempted, at the series and stage levels, particularly when the major outcrops are all separated.

Fauna and Flora

The rich ammonoid faunas of Kutch Jurassic together with those of the Tethys Himalaya have a significant bearing on the nature and extent of faunal provinces within the Tethyan realm as also on the marine seaways connecting them. Biogeographical reconstructions made with the available data invariably present a direct and often persistent marine connection at least from Toarcian (late Early Jurassic) onwards from East Africa, Madagascar, Kutch, Jaisalmer, Salt Range, Spiti, Malla-Johar, Nepal, south Tibet as also Sula Islands to New Guinea. All these are characterised by restricted common ammonoids through the successive stages and sub-stages, at least until the close of the Lower Tithonian (late Upper Jurassic). These belong to the Ethiopian Faunal Province. The Callovian stage in Kutch is considered to be the one best developed in the world, while Kutch Jurassic sequence as a whole is considered of primary reference in the entire East Tethyan region. Table 8.4 presents an updated Ammonoid zonation in the Jurassic of Kutch in relation to those established in the Mediterranean region.

Earliest known occurrence of nannofossils, the tiniest (diameter - 1 to 30 μ) marine calcareous microfossils, are from Early Jurassic. These ultra-microscopic bodies are the skeletal elements produced by the flagellated, unicellular golden brown phytoplankton called Coccolithophores. After the death of the organism these skeletal elements are mostly detached and deposited at the bottom of the ocean and thus supply large quantities of biogenic rock matter. The broad groups that are included in the study of nannofossils are the extant Coccolithophorids and the extinct discoasters and nannoconids. Nannoflora of the Chari Series has proven to be the best known in the world.

In general, ostracoda from Kutch and Rajasthan show a strong affinity with those known from Madagascar (Majunga Basin) and South Africa, while the Upper Jurassic ostracoda from Spiti have affinity with those of Western Europe. East Coast Cretaceous ostracoda show a strong affinity with European Biogeographic Province. About 28 species of ostracodes are reported from the Jurassic beds of Jumura dome (Kutch) – ranging from Bathonian to Oxfordian.

First record of fossil Holothurian sclerites is from the rocks of Jurassic age. These are recovered from the rocks of Khadir and Goradongar Formations of Middle Jurassic (? Callovian) age. The suite belongs to families *Priscopedatidae* Frizzel and Exline and *Protocaudinidae* Deflandre.

The oldest ammonoids are *Leptoshiphinctes* (Bajocian) and *Clydoniceras* and *Macrocephalites* (Bathonian) from the lower part of Patcham Series. New finds of *Cleoniceras* and *Lemuroceras* extend the age of Ukra Stage from Aptian into Lower Albian.

In Waagad, outside the Kutch mainland, is found exceptionally rich ammonoid fossils at Kankote in mid- Middle Oxfordian stratigraphic interval. It is made up of 10 m thick successions of 13 ammonoid levels.

The following palynofossils are reported so far from the Series:

Chari: *Araucariacites, Gleichniidites, Callialasporites, Alisporites, Contignisporites, Podosporites*

Katrol: Besides the above, *Microcachryidites classopolis, Vitreisporites*

Umia: *Araucariacites, Callialasporites, Alisporites, Podosporites, Lycopodiumsporites, Microcachryidites, Impardecispora, Psilospora, Murospora, Densiosporites*

There appears to be a more or less smooth transition in the palynofloral composition from Late Jurassic to Early Cretaceous i.e. from Tithonian to Berriasian.

Rajasthan

The Lathi Formation, exposed in Jaisalmer district at Odania and Thaiat (Fig.8.14), is mainly an arenaceous sequence of ill-sorted sandstones, ferruginous siltstones, purplish white clay and conglomerate. It is divided into two members, Thaiat and Odania. The exposed thickness is around 350 m and becomes more argillaceous in the basinal part. The floral remains reported include fossil wood belonging to gymnosperm and leaf impression of *Pterophyllum* sp., *Ptilophyllum acutifolium* and *Equisetites* sp. Considering the litho-logical characters and floral remains, a fluvio-deltaic environment is suggested. The age is early Jurassic (Liassic) probably extending into Bathonian.

The isolated, eroded and horizontally bedded outcrops around Jaisalmer city, NW of Thaiat and Kuldhar-Dujero Dungar belong to the Jaisalmer Formation. The sharp lithological contrast between variegated clays and non-calcareous sandstone of Lathi Formation and calcareous sandstone and

Table 8.4. Update on Kachchh Jurassic ammonoid chornology and sequence stratigraphy (modified after Jai Krishna, 2005, p.77)

STAGES		CARIOU AND HANTZPERGUE 1997 NORTH TETHYAN MARGIN		2nd & 3rd ORD SEQS.		REVISED AFTER KRISHNA 2002,KRISHNA &OJHA 1996 & KRISHNA etal.1996ab SOUTH TETHYAN MARGIN (KACHCHH)			AGE IN MA
		ZONES	SUBZONES			SUBZONES		ZONES	
TITHONIAN	LATE					OPPELI		VIRGATOSPHINCTES DENSIPLICATUS	141.2
		MICROCANTHUM	TRANSITORIUS			FREQUENS			
			SIMPLISPHINCTES			DENSIPLICATUS			
	EARLY	PONTI				SUBFREQUENS		VIRGATOSPHINCTES COMMUNIS	
						COMMUNIS			
		SEMIFORMIS				KRAFTI		AULACOSPHINCTOIDS NATRICOIDES	
						POMPECKJI			
						DOGHLAENSIS			
						NATRICOIDES			
		DARWINI	PALATINUS			BIPLICATUS		KATROLICERAS VIRGATOSPHINCTOIDES	
			VIMINEUS			RAJNATHI			
			TRIPLICATUS			PEERINSMITHI			
		HYBONOTUM				SPARSICOSTA		KATROLICERAS POTTINGERI	T1-T17 HORIZONS
						POTTINGERI			
KIMMERIDGIAN	LATE	BECKERI				INFUNDIBULUM		KATROLICERAS KATROLENSIS	148.2
						INVERSUM			
						PRESSULUM			
						KATROLENSIS			
		EUDOXUS				LINGUIFERUS		TORQUATISPINCTES BATHYPLOCUS	
					R	BATHYPLOCUS			
		ACANTHICUM				IPHICEROIDES		TORQUATISPINCTES INTERMEDIUS	
						ACANTHICUM			
	EARLY	DIVISEUM	UHLANDI			KACHHENSIS		TORQUATISPINCTES ALTERNEPLICATUS	
			TENUICOSTATUM	T		ALTERNEPLICATUS			
		HYPSELOCYCLUM	LQTHARI			? ATAXIOCERAS	ZONATION IN PROGRESS	?	K1-K19 HORIZONS
			HIPPOLYTENSE						
		PLATYNOTA	GULHERANDENSE						
			DESMOIDES						
			POLYGYRATUS						
OXFORDIAN	LATE	PLANULA	GRANDIPLEX			ORTHOSPHINCTES			153.3
			PLANULA						
		BIMAMMATUM	HAUFFIANUM			?			
			BIMAMMATUM						
			BERRENSE			? BERRENSE			
			SEMIMAMMATUM			?			
		BIFURCATUS	GROSSOUVREI			GROSSOUVREI		DICHOTOMOCEQAS BIFURCATUS	
			STENOCYCLOIDES			STENOCYCLOIDES			
	MIDDLE	SCHILLI	ROTOIDES			ROTOIDES		LARCHERIA SCHILLI	
			SCHILLI	R		SCHILLI			
		TRANSVERSARIUM	LUCIAEFORMIS			?'	ZONATION IN PROGRESS	?	
			PARANDIERI						
		PLICATILIS	ANTECEDENS						
			VERTEBRALE			INDOGERMANUS			
	EARLY	CORDATUM	CORDATUM			SEMIRUGOSUS			
			COSTICARDIA		T	DHOSAENSE			
			BUKOWSKII			DELMONTANUS			
		MARIAE	PRAECORDATUM			SECULA			
			SCARBURGENSE			BERNENSIS			
CALLOVIAN		LAMBERTI	LAMBERTI			?		?	159.2
	LATE	ATHLETA	POCULUM			PONDEROSUM		PELTOCERAS ATHLETA	
			COLLOTIFORMIS			DEPRESSUM			
			TREZEENSE			PSEUDORION			
	MIDDLE	CORONATUM	ROTA			CATILLUS		KINKELINICERAS OBTUSICOSTA	
			LEUTHARDTI			OBTUSICOSTA			
			BAYLEI						
		ANCEPS	TYRANNIFORMIS			PARAMORPHUM		REINECKEIA ANCEPS	
					R	KLEIDOS			
			STUEBELI			RAMOSA			
						OPIS/EUCYCLUM			
	EARLY	GRACILIS	PATINA	T		SEMILAEVIS		MACROCEPHALITES SEMILAEVIS	
						FORMOSUS			
			MICHALSKII			DIADEMATUS		MACROCEPHALITES CHRYSOOLITHICUS	
			LAUGIERI						
			PICTAVA			CHRYSOOLITHICUS			
			GROSSOUVREI						
			PRAHECQUENSE			TRANSITORIUS			C1-C25 HORIZONS
		BULLATUS	BULLATUS			MADAGASCARIENSIS		* MADAGASCARIENSIS	
BATHONIAN	LATE	DISCUS	DISCUS			TRIANGULARIS			164.3
			HOLLANDI			CLYDONICERAS			
		RETROCOSTATUM	HANNOVERANUS			HANNOVERANUS			
			BLANAZENSE						
	MIDDLE	BREMERI	FORTECOSTATUM			MICROMPHALITES			
			BULLATIMORPHUS			BULLATIMORPHUS			
		MORRISI	MORRISI					?	
		SUBCONTRACTUS	SUBCONTRACTUS						
		PROGRACILIS	PROGRACILIS	R	T	WAGNERICERAS			
			ORBIGNYI						
	EARLY	AURIGERUS	TENUIPLICATUS			EBRAYICERAS			
			RECINCTUS						
		ZIGZAG	MACRESCENS						
			PARVUM			AMMONOID DEVOID	ZONATION IN PROGRESS		
BAJOCIAN	LATE	PARKINSONI	BOMFORDI						169.2
			DENSICOSTA						
			ACRIS						
		GARANTIANA	TETRAGONA			AMMONOID DEVOID			
			SUBGARANTI	T					
			DICHOTOMA						
		NORTENSE/ SUBFURCATUM	BACULATA						
			POLYGYRALIS			LEPTOSPHINCTES			172.8

* MACROCEPHALITES

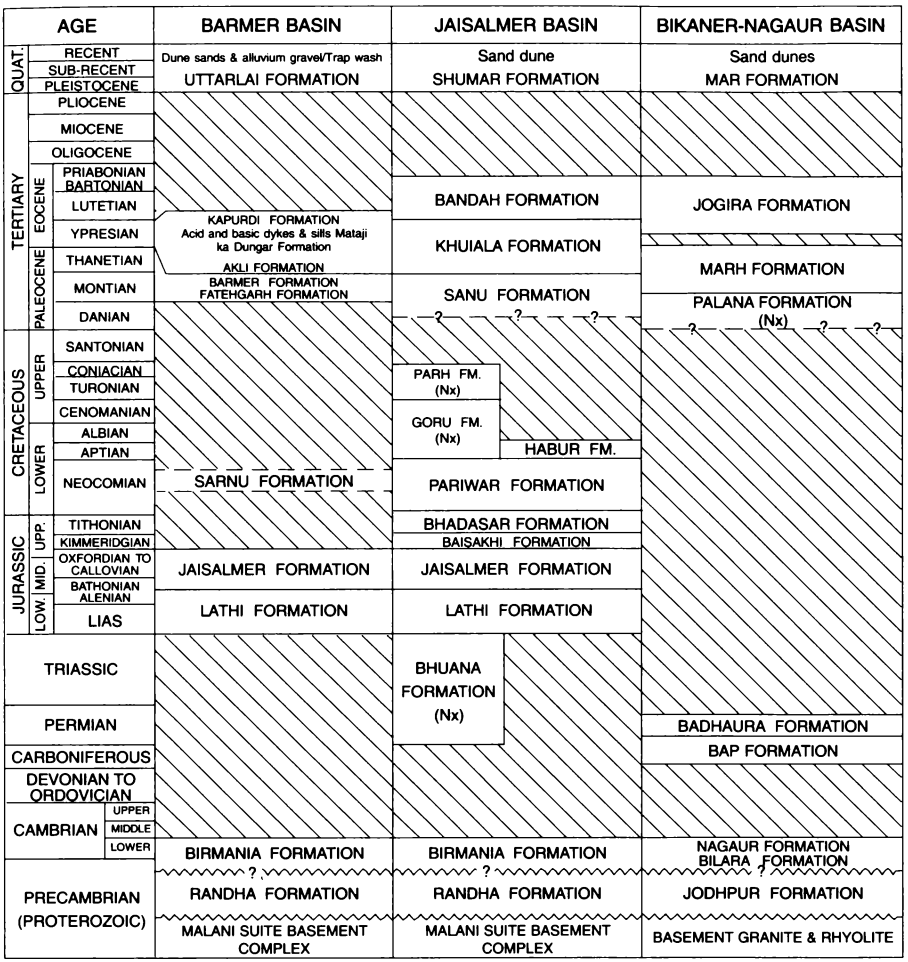


Fig.8.14. Correlation of lithostratigraphic units of western Rajasthan Basins (after Pande and Dave, 1998). Nx - Not exposed.

limestone of Jaisalmer Formation helps to distinguish these in the field. Alternations of marine arenaceous limestone and calcareous sandstone with a fossiliferous oolitic bed at the top are the dominant lithology of this unit. Maximum thickness is around 400 m. Megafossils reported are *Reineckeia* sp., *Reineckeites* cf. *waageni*, *Indosphinctes* sp., *Kinkeliniceras* sp., *Mayaites* sp., *Obtusicostitis* cf. *nandi*, *Epimayaitis* cf. *excentricus* and *Dhosaites* aff. *otoitoides*. Microfossils noted are *Lenticulina delicataformis*, *Astacolus apherastus* and *Trocholina transversarii*. Besides these, bryozoans, corals (rare) and serpulids have also been recorded. The age of this formation is Callovian-Oxfordian. An open marine stable shelf with minor fluctuating condition of deposition is envisaged for this unit.

The Jaisalmer Formation is overlain by Baisakhi and Bhadasar Formations.

The scarp section west of Baisakhi and Rupsi exposes Baisakhi Formation and the scarp at Bhadasar exposes the latter.

Formation	Lithology	Fauna
Bhadasar Formation	Fossilliferous oolitic grits, calcareous sandstone	*Lorquatisphisctes tenuistriata, L. labyensis, L. rebillyi, Katroliceras deprecssune*
Baisakhi Formation	Grey to black gypseous shale, argillaceous sandstone, intraformational conglomerate	

The age assigned for Bhadasar/ Baisakhi Formations is Kimmeridgian. Sedimentation under normal open marine condition changing into high-energy near-coastal condition (as inferred by fossil wood and cross-bedded sandstone at the top) is suggested.

Jammu and Kashmir

Jurassic rocks, designated as the Drumgam Formation, have been discovered from the Warwan valley, Doda district, Kashmir Himalaya. They occur as isolated outliers resting unconformably over Wuyan Formation (Triassic) intermittently over a strike length of 10 km with an average width of one km lying on the crestal part of the Great Himalayan Range at altitudes ranging from 3700 to 6000 m above msl in Drumgaon-Kelnar area.

Drumgam Formation	Member B	Sandy calcareous shale	*Belemnopsis* sp. of *B. gerardi*	Middle to Late Jurassic
	Member A	Quartzite, greywacke and slate	*Belemnopsis gerardi*	Middle Jurassic

Member A is correlatable with Upper Katrol of Kutch and Member B with Lower Umia of Kutch and Spiti Shale of Spiti.

In the wide syncline near Baltal on the upper Sind river, ENE of Srinagar, the Upper Triassic passes upwards into a series of contorted dark pyritous slates with thin limestone containing indeterminable remains of ammonites and of rod-like bodies (belemnites) of Jurassic.

Ladakh: There is a large exposure of Jurassic rocks in the core of the syncline in Zanskar-Rupshu area, in Ladakh. In a few places, it is underlain by dolomitic limestone of Tagling Stage, which passes at many places conformably

into Spiti Shales of Upper Jurassic age. These rock types form a broad basin of marine Mesozoic rocks situated on the inner flank of the Zanskar Range and are connected with Jurassic rocks of Spiti by continuing along the strike. The common faunas met with in these formations comprise cephalopods, bivalves and brachiopods.

For over a century the Late Jurassic-Early Cretaceous platform carbonate succession on the south Tethyan margin (inclusive of the Himalayan belt) has defied precise dating due to lack of guide fossils. Recently a Hettangian *Psiloceras* (Jurassic *ammonitina*) (lowermost Jurassic) has been discovered in the deep marine sediments of the Lamayuru Formation in Ladakh Himalaya. The newly discovered ammonoid bearing 10 m interval is developed in a clastic facies (shale/siltstone) and may be related to a widely expressed rifting-cum eustatic event of Vail cycle UAB 1.

Eastern Karakoram: The Margo Formation of Triassic gradually passes upward into a sequence of grey-pink limestone with bands of gypsum, dolomite, cherty limestone, chert, shale and siltstone of the Burtsa Formation (Fig.6.13). The carbonates contain sponge spicules and foraminifera of the pelagic facies. This formation contains important fossils of *Daonella, Halobia, Syringotheria* and *Stoliczkaria.* Most of the fossils are of Triassic age. In Karakoram Pass the sedimentary succession is comparable with the Jurassic sandstone of Shaksgam in the Sinkiang Province of China.

Himachal Pradesh

Spiti: The name Lagudarsi Group has been suggested for the rock formations above Lilang Group. This group is made up of Spiti Formation, Giumal Formation and Chukku Formation of which the Spiti Formation overlying Kioto Limestone of Lilang Group extends from Oxfordian to Tithonian. A good section, of these three formations, is well exposed between Chichum and Latarse (Table 8.5).

Spiti Formation: The name Spiti Shale was originally proposed by Stoliczka. The formation is exposed in several isolated synformal outliers. At Sachibang (Lingti Valley) the sequence of the Spiti Formation begins with one or two metre thick grey lenticular ferruginous fine-grained sandstone and/or siltstone. This is unconformably overlain by the Kioto Formation. Over this, Spiti Formation rests along a sharp contact.

The Spiti Formation comprises black shale tending to be splintery, fine-grained sandstone and siltstone. In some sections phosphatic and calcareous nodules enclose fossils. The black shales sporadically show gypsum scales.

Ichnogenus *Zoophycos* and other pelagic nektonic body fossils (cephalopods) are of common occurrence. The important fossils in the formation are:

Brachiopods: *Rhynchonella* aff. *lacunosa, Terebratula*
Cephalopods: *Epimayites lemoini, Prograyiceras grayi,Grayiceras koeneni, Mayites waagens, Belemnopsis gerardi*
Bivalves: *Inoceramus* cf. *sularum, Lima melaancholica, Lima tristicula, Nuculu spitiensis, Asteria schenko*

The Spiti Formation was deposited through a slow rate of sedimentation on shelf mud environment. The basin witnessed occasional mudflows and frequent hard ground formation.

Uttarakhand

The Kiogad Formation in the Niti area in Uttarakhand is made up of Lapthal, Chhojan and Spiti Members in ascending order. The palyno-assemblage and the other fauna with age are also given in the Table 8.2. It has been found that Laptal and Spiti Members contain some reworked palynofossils as well.

Laptal: *Plicatipollenites, Striatites, Sahnites*
Spiti: *Plicatipollenites, Striatopodocarpites, Cuneatisporites*

A rich assemblage of dinoflagellate cysts and acritarchs along with some spores and pollen grains are recovered from parts of Spiti Shale near Laptal in Malla Johar, Pithorgarh district. Kimmeridgian-Tithonian age is suggested.

Jharkhand

Rajmahal Basin: The lowermost first inter-trappean bed within the Rajmahal Trap and the infra-trappean bed, just below the Trap (ca.118 Ma) from the Rajmahal basin, Jharkhand contain most of the forms found in the Laptal Member in Niti (Uttaranchal), together with the other newer elements. The continuity of these palynomorphs from Callovian (Laptal) to Aptian (Rajmahal) is very significant.

Bhutan

In the Bhutan Himalaya, the Late Jurassic-Early Cretaceous Lingshi Formation is preserved in three isolated synclines. The formation is represented by an argillo-arenaceous sequence, in which are present marine and also plant fossils. The sequence is regarded to have been deposited in a near estuarine/ tidal flat, where plant fragments could drift without getting damaged.

Table 8.5 Ammonoid biostratigraphy of Spiti Formation around Chichim and Gaitey-Spiti Tehsil, Himachal Pradesh (after Pathak, 1997) (source: Srikantia and Bhargava, 1998, opp. p.250)

System	Stage	Substage	Formation	Bed (Thickness)	Ammonoid Assemblage	Ammonoid species Recorded	Remarks
CRETACEOUS	BERRIASIAN	LOWER	GIUMAL FORMATION	15 (40 M)	Odontodiscoceras	*Odontodiscoceras* gr. *odontodiscus*, *Berriasella* sp., *Neocomites* sp.	The appearance of the genera *Neocosmoceras*, *Neocomites*, *Berriasella* etc. indicate beginning of Cretaceous in the area
				13-14 (10 M)	Neocosmoceras	*Neocosmoceras* gr. *octagonus*, *Spiticeras* sp., *Kilianella* sp. *Berriasella* sp., *Odontodiscoceras* gr. *odontodiscus*,	
JURASSIC	TITHONIAN	UPPER	SPITI FORMATION	12 (90 M)	Himalayites	*Himalayites* gr. *seideli*, H. Sp., *Virgatosphinctes densiplicatus*, v. sp., *Aulacosphinctes* cf. *latauchei*, *Kossmatia tenuistriata*, K. aff. *koeneni*, *Blanfordiceras cricki*, *Spiticeras eximius*, S. aff. *bulliformis*	*Himalyites* is known from Upper Tithonian of Malla-Johar (Krishna et al. 1982) and Spain (Tavera, 1985) while *V. densiplicatus* with *Aulacosphinctes* are known from Upper Tithonian of Kachchh Mainland (Spath, 1927-33)
				10-11 (Gaitey) 12 (50-60 M) (Chichim)	Virgatosphinctes	*Virgatosphinctes communis*, V. spp., *Aulacosphinctes* cf. *latauchei*, *Blanfordiceras* aff. *wallichi* *Kossmotia tenuistriata* K. aff. *Koeneni*, *Spiticeras eximius*, S. aff. *bulliformis*	*V. communis* with *Aulacosphinctes* and *Micracanthoceras* is known from Upper Tithonian of Western part of Kachchh Mainland (Spath, 1927-1933)
		LOWER	SPITI FORMATION	9 (40-50 M)	Spiticeras	*Spiticeras indicus*, S. *guttatus*, S. *spitiensis*, S. cf. *subspitiensis* S. aff. *eximux*, *Aulacosphinctoides sparsicosta*, A. aff. *linoptychus*, *Hildoglochiceras kobelli* *Paraboliceras mutilis*, *P. griesbachi*, *Paraboliceratoides* sp., *Kossmatia tenuistriata*, K. *desmidoptycha*, *Uhligites* aff. *adunta*, U. spp., *Gymnodiscoceras griesbachi* and *Holcophylloceras* aff. *mesolcum*	*Spiticeras* appears first at this level in late Lower Tithonian as indicated by species association. Earlier it was known from late Upper Tithonian in Europe and elsewhere
				7-8 (30 M)	Aulacosphinctoides/ Paraboliceras	*Aulacosphinctoides* aff. *uhligi*, A. aff. *linoptychus*, A. sp., *Katroliceras pottingeri*, *Subdichotomoceras* sp., *Hybonoticeras hybonotum*, *Paraboliceras polysphinctus*, P. *himalayanus*, P. *criptoptychus* P. *rectacostatus*, P. *tibaticus* P. *suineanus*, *Kossmatia desmidoptycha* K. *teneuistriata*, K. sp., *Uhligites* sp. *Gymnodiscoceras griesbachi* and G. *lymani*	*Aulacosphinctoides*, *paraboliceras* and *Kossmatia* are the dominating genera. The presence of *Hybonoticeras hybonotum* marks the beginning of Tithonian
	KIMMERIDGIAN	UPPER	SPITI FORMATION	5-6 (40 M)	Pachysphinctes	*Pachysphinctes linguiferus* P. *granti*, *Aspidoceras* cf. *subwynnei*, *Paraboliceras polysphinctes*, *Streblites* aff. *plicodiscus*, *Taramelliceras* sp.	*Paraboliceras* appears here. The species of this assemblage have been known from Upper Kimmeridgian of Western India, Pakistan, Madagascar etc. (Krishna and Pathak, 1991 and 1993)
				3-4 (30 M) (Gaitey) 2-3 (30 M) (Chichim)	Torquatisphinctes	*Torquatisphinctes torquatus*, T. *inetermedius*, *Aspidoceras iphiceroides*	The species of this assemblage are dated as of early Late Kimmeridgian age (Krishna and Pathak, 1991 and 1993)
	OXFORDIAN				Mayaites	*Mayaites Waageni*, *Epimayaites*, sp.	It is the oldest ammonoid assemblage of the Spiti Shale abundant in Lower Oxfordian of Kachchh (Western India)

KIOTO FORMATION (LILANG GROUP)

CRETACEOUS

Rocks of Cretaceous period have a span of about 80 Ma, extending from 145 to 65 Ma ago. Compared to those of Triassic and Jurassic, the marine Cretaceous, besides being present in the Himalayan Tethyan belt, is also met with in Narmada basin in Central India, Trichinopoly area in Tamil Nadu and in North-Eastern India. However, in most of the areas, only part of the system is represented. It is a major marine transgression that brought in sediments in the Narmada basin and Trichinopoly area (Cauvery basin), though there were quite a few minor transgressions and regressions within these.

Chronostratigraphically, the most relevant and significant in the Cretaceous are the ammonoids, rudistids, and microfossils, dinoflagellates and coccoliths. The dinoflagellate cysts and microfossils have been useful in precisely dating Cretaceous to Early Eocene sediments in the Cauvery basin.

Kutch

The Umia Stage consists mainly of barren sandstone with fossiliferous intercalations. The Ammonite Beds, about 5 m thick are green oolites with abundant ammonites. Large *Virgatosphinctes* is the characteristic ammonite but *Aulacosphinctes, Ptychophylloceras, Umiaites* and *Microacanthoceras* also occur. Other fossils are *Acanthorhynchia*, *Lobothyria* and *Trigonia.* This stage may extend from Upper Tithonian to Neocomian. The succeeding Ukra Stage is made up of mainly calcareous shale of Aptian age, with a few ammonite fossils. The Bhuj sediments at the top contain a few plant fossils, the horizon being called Umia Plant beds, of post-Aptian age. In order to eliminate confusion in the use of chrono- and lithostratigraphic nomenclature, Biswas (1971, 1991) defined *sensu stricto* rock stratigraphic units based on detailed mapping. He christened thick sandstone dominated Lower Cretaceous deltaic sequence as Bhuj Formation 1000 m (+) and sub-divided it into three members, developed only in Western Mainland.

Upper Member	Albian 480 m (+)
Ukra Member	Aptian 35 m
Ghuneri/Lower Member	Neocomian 600 m
(West) (East)	

Towards east only Lower Member is present as the Ukra Member pinches out and the Upper Member is mostly eroded off. The environments of Lower and Ghuneri Member is considered to be a lower deltaic plain (distributary), that of Ukra, a restricted bay or lagoon and that of the Upper Member- a fluvial, upper deltaic plain.

The following trace fossils and burrowing patterns have been recognised in the Bhuj region:

Skilolithos – Vertical burrows
Rhizocorallium - > > (horizontal)
Diplocraterion - U-shaped
Thalassinoides – burrows - Y-shaped
Inclined sand filled burrows
Sand filled burrows in carbonaceous shales

Bioturbated medium to coarse sand horizons represent a distinct lithofacies, which is persistent laterally. The occurrence of the following three ichnogenera, namely *Skilolithos* Haldermann, *Planolites* Nicholson and *Thalassinoides* Ehrenburg are indicative of littoral marginal marine environment for the deposition of the Bhuj Formation.

The mega-flora in Umia Beds are: *Ptilophyllum, Williamsonia, Elatocladus, Araucarites, Brachyphyllum, Cladophlebis, Gleichenia, Onychiopsis, Matonodium, Equisetites.*

The microflora are *Araucariacites, Calliaspirites,* and *Alisporites* (Neocomian-Aptian). *Hystrichosphaeridium* and *Hystrichosphaeris* from Ghuneri and *Gleichniidites cicatricosisparites* and *Foraminisporis* from Bhuj Member are reported.

The Bhuj sandstones in Kutch basin represent deltaic deposits. Sandstones are dominantly micaceous feldspathic wackes with both fresh and altered feldspars. The secondary wacke matrix has been derived from alteration of feldspars. High degree of ferrugination is seen in almost all the sandstones. Tabular and planar cross-bedding predominate in sandstones with occasional herring-bone structures excepting in the western part where wave-built hummocky and cross-bedding are seen. A characteristic feature of Bhuj Sandstone is highly bioturbated ferruginous bands at rhythemic intervals. This marks the end of sedimentation cycles in the delta front zone.

Several plug-like bodies have been located in the Pachham and Mainland intruding the Mesozoic rocks. Olivine nodules and mantle xenoliths are common in the alkali basalts indicating that the intrusive magma came from mantle depth. Some plugs are gabbroic complexes, with diorite, lamprophyre and syenite. These intrusives are rift related syntectonic plutonic activities unrelated to Late Cretaceous Deccan Trap volcanism, which marks the end of Mesozoic history of the basin.

Radiometrically glauconites from Ukra Member have been dated by fission track technique: 112 Ma (= Early Aptian).

Saurashtra

In the northeastern part of Saurashtra occur sedimentaries, which were divided into Dharangadhara and Wadhwan Formations. These have been designated together as Dharangadhara Group, though such a nomenclature is not acceptable according to Code of Stratigraphic Nomenclature. Earlier these have been described as Kathiawar Beds. These cover about 500 km^2.

An estimated 600 m thick succession of sedimentary rocks ranging from Late Jurassic to Early Cretaceous (Upper Tithonian to Albian: 145-97 Ma) represents the Mesozoic rocks of Surendranagar-Wankaner district in Saurashtra basin. Around Surendranagar, these rocks extend in the subsurface underneath the alluvium and Deccan basalt. These predominantly terrigenous rocks consist of interbedded sandstone with local lenses of conglomerate, shale and siltsone. There are also beds of carbonaceous shale with occasional coaly stringers in the basal part and fossiliferous calcareous lenses in the upper part. The formations display shallow dip 3 to 8° in most of the places. The designated sequence of Than (~125 m), Surajdeval (~175 m), Ranipet (~200 m) and Wadhwan (>50 m) Formations are assigned to the Dharangadhara Group.

Fossil plants *Matonidium geopperti, Weichselia reticulata, Onpehiopsis psilotoides* and *Cladophlebis denticulate* are recorded from Than Formation containing carbonaceous shale with or without coal, siltstone and sandstone. Lenses of limestone within Wadhwan Formation contain invertebrate body fossils *Pycnodonta bouchevoni, Crassostrea scidiformis, Protocardia pauli* and *Spondylus latus* similar to those found in nearby Bagh Beds of Narmada valley. A rich assemblage of pteridophytes, lycopods, cycads and angiosperms is also reported. The rich microflora (spores and pollen) point to an age ranging from uppermost Jurassic (Tithonian) to Lower Cretaceous (Neocomian), extending probably up to Albian.

The bulk of the lithofacies including their sedimentary characters, represents deposition in the nearshore coastal delta plain with a gradual north-eastward transgression documented by the facies transition from Than to Wadhwan Formations.

Rajasthan

The Cretaceous sequence in Jaisalmer basin commences with Pariwar Formation (Fig.8.14) unconformably overlying the Bhadasar Sandstone of Upper Jurassic. It is a sequence of variegated silty sandstone, besides pebbly sandstone and conglomerate at the base. The entire formation is about 300 m thick in the scarp, west of Habur in the type area. The Pariwar Sandstone

contains fossils of *Taeniopteris vittata, Ptilophyllum acutifolium, Otazamites imbricatus, Elatocladus conferta* and *Mesembrixylon* (fossil tree trunk) indicating Lower Cretaceous – Neocomian age.

It is from the shallow-drilling data that the existence of Goru and Parh Formations, above the Pariwar Formation came to be recognised. The Goru Formation, made up of shales with sandy lenses, contains angiosperm pollen in its upper part. This is assigned Albian to Cenomanian age. The Parh Formation of Coniacian age is dominantly made up of greenish-grey argillaceous limestone and marl.

The succeeding Habur Formation has faulted contact with the underlying Bhadasar Formation and consists of coquinoidal limestone and calcareous sandstone. Presence of *Deshayesites bodei* in the basal section fixes its lower limit as Lower Aptian. Forms assignable to *Sarasinella* sp., *S. subspinosa* are also reported from this unit. Nearshore marine environment is suggested for this unit, which has a thickness of about 200 m.

The importance of glauconites in dating is that they are formed under low sedimentation rates connected with marine transgression and are commonly associated with unconformities and other stratigraphic breaks. Rb-Sr age of 108±5 Ma and average K-Ar age of 103±3 Ma obtained for the glauconitic mica group from Goru Formation (subsurface core) are indistinguishable within error and agree with their biostratigraphic age. Glauconites from the upper part of the Pariwar Formation give an average K-Ar age of 106±3 Ma (early Albian), which is slightly lower than their biostratigraphic age. Such minor differences result from argon loss and mobility and when combined with Rb-Sr age these differences are narrowed down.

Barmer basin in the northernmost part of Cambay rift basin occurs to the southeast of Jaisalmer basin as a narrow north-south trending graben, which extends over 100 km from Mandi in the north to Barmer in the south. The Fatehgarh Formation in the basin comprises a sequence of conglomerate, sandstone, bentonitic clay, and phosphatic sandstone and mudstone. The basal polymictic conglomerate containing clasts of quartzite, Jalor granite and Malani rhyolite marks the unconformity between the Fatehgarh rocks and the underlying Lathi Formation (see Fig. 8.14). The Fatehgarh Formation is overlain by 5 m thick Bariyara Member of Mataji-ka-Dunger Formation characterised by siliceous earth, which could be the result of either Cretaceous-Tertiary volcanic episode or the meteoric impact event that formed the "Shiva Crater". The sequence has a thickness of 70 m and is tectonically truncated in the north by the Fatehgarh fault. The fossil assemblage includes gastropods, lamellibranchs, ostracods, fish scales, and fish teeth.

Bikaner-Nagaur basin does not seem to contain any Mesozoic sediment.

Jammu and Kashmir

The Mesozoic is represented by sediments, volcanics and ophiolites in the Indus Tectonic Zone of Ladakh, also referred to as the Indus Suture Zone. These rocks are grouped under the Sangeluma Group which extends geographically from Nanga Parbat region in the northwest to Astor-Burzil, Dras-Kargil and along the Indus valley and thence to Hanle and beyond along the Tsangpo valley in Tibet for a length of over 2500 km. It represents an important collisional zone in the Himalaya.

The Sangeluma Group represents a thick sequence of sediments and lava flows in which slices of ophiolite blocks are tectonically emplaced. It has been thrust over the Ladakh Granitoid batholith and the Neogene sediments of the Indus Group. The Sangeluma Group, though divisible into four formations, only the basal Khalsi Formation and the succeeding Dras Volcanic Formation are Cretaceous in age though the latter may extend into Paleocene. The upper Nindam Formation and the Shergol Formation belong to the Cenozoic.

The Khalsi Formation is characterised by an association of *Orbitolina* bearing limestone, grey splintery shale, calcareous phyllite, lenticular conglomerate, gritstone, green chert beds, volcanogenic sediments, tuffaceous shale and minor quartzarenite. The formation enclosed tectonic slices of ophiolite. The Khalsi Formation has yielded *Orbitolina* sp. along with bivalves, corals, gastropods, echinoids and crinoids. The important fossils are *Orbitolina kashmirica, O. pileus, O. parma, O. discoidea, Cytherella* sp., *Protocytherella* sp., *Cenomanella archiaciane, Ludbrookia* sp., *Lepidocorbitoides* and *Damesia cretacea*. Broadly the fossil assemblage indicates an Albian-Cenomanian age.

The Dras Formation has been deformed, metamorphosed and intruded by diorites, which are dated 104 Ma. Here the deformation, metamorphism and granitisation are more or less contemporaneous with sedimentation. This demonstrates the contemporaneity of these phenomena in the Tethyan belt. An ammonite fragment, *Oxytropidoceras (Micropelia) douglasi* Knechtel, has been recovered from black shales intercalated at the metamorphic volcano-sedimentary Dras Formation near Trespone (south of Kargil, Suru Valley, Ladakh). This fragment gives a middle Albian age to the Dras Formation. The fossils of *Orbitolina*, radiolarians and bryozoans, however, indicate Barremian to Cenomanian age. One specimen of *Hippurites* is also reported.

Dras Volcanics: These occur in the form of synclinal outliers, inverted at many places, and extend from southeast of Burzil river through Minimarg to Dras and beyond to Changthang area. This belt cuts obliquely across the great Himalayan range. The rocks include marine sediments as well as volcanic, pyroclastic, hypabyssal and plutonic rocks. Southeast of Dras and in Changthang

area gabbros, pyroxenites, peridotites and serpentinites intrude in the form of sills, dykes and bosses, penetrating Dras Volcanics, stratified tuffs, ash beds and basaltic flows.

The ophiolite melange consists of chert, cherty shale, jasperite and occasional limestone and belongs to the Indus ophiolite belt sandwiched between the Kashmir-Rupshu basin to the south and Ladakh granitic mass with its sedimentary cover to the north. *Globotruncana* and *Heterohelix* (foraminifera) in a shale bed indicate an Upper Cretaceous age.

The volcanic rocks in Dras contain thin limestone bands carrying *Dictyoconoides, Alveolina* (foraminifera) and Eocene gastropods, which imply that the age of Dras Volcanics ranges up to lower Eocene. Undoubted radiolarian fossils have been discovered in the chert bands associated with the volcanics. The Dras Volcanics are probably the result of submarine eruptions, which occurred during a marine submergence at the close of the Late Cretaceous and Early Eocene times. By mid-Eocene time the activity appears to have ceased as the marls and the nummulitic limestones of that age have remained unaffected by the volcanic activity.

Eastern Karakoram: Many tectonostratigraphic units represented by igneous, sedimentary and metamorphic rocks are sandwiched between the Ladakh batholith to the south and the Karakoram batholith to the north. Of these, the Hundri Formation represents the Shyok tectonic belt, now called as Shyok suture, in Eastern Karakoram. Lithologically, this unit is constituted mainly by massive grey limestone in the lower part and carbonaceous shale and grey to green shale in the upper part. This unit has yielded several age diagnostic foraminiferal taxa indicating an Aptian-Albian age. The fauna includes several species of *Palorbitolina, Mesoorbitolina, Orbitolina, Tibetella, Praeorbitolina* and *Alpilina*, in addition to a few taxa of algae, bryozoans and corals.

The Shyok suture zone, earlier called as a tectonic unit, lies to the north of the Indus Suture Zone and is separated from the latter by the intrusive Ladakh Granitoids (Late Cretaceous – Early Eocene) to the south and Karakoram Granitoids to the north. This zone lies south of Karakoram block and is constituted by ophiolitic, sedimentary and metamorphic rocks. The Hundri Formation represents the volcano-sedimentary and marine sedimentary successions in this belt. The Orbitolina limestone of this unit has yielded several Aptian-Albian orbitolinids.

A thick sequence of red conglomerate with interbedded carbonaceous shale, sandstone and thin-bedded limestone occurs called Qazil Langer Formation (Fig.6.13). The reported occurrence of *Globigerinoides* and *Textularia* assigns a Cretaceous age to this formation.

Himachal Pradesh

Giumal Formation: This occurs in Spiti area with a gradational contact with the Spiti Formation of Oxfordian to Tithonian age and is exposed as synformal outliers at the Lagudarsi Pass, Domal (old Giumal), Langja and Sakti synclines. It consists of sandstone, siltstone, silty shale and shale with local conglomerate lenses. Body fossils and trace fossils are found in the basal part of the sequence of sandstone with calcareous intercalations. In the upper part, two to three beds of fine-grained dark green glauconitic sandstone appear. Important fossils found in this formation are: *Cardium giumalense, Ostrea* sp., *Gryphea* aff. *baylei*, *Pecten* sp., *Tellina* cf. *strigata, Pseudomonotis*. Ammonoid species are also present. The terebratulids recovered from the lower part of the Giumal Formation are the earliest brachiopods recorded from the Cretaceous of the Tethys Himalaya.

The Giumal sandstone with intercalated black shale in basal part indicates extension of the environment identical to that of Spiti Formation. The basin gradually became open marine. The presence of marine water of normal salinity and organic matter led to the right condition for the formation of glauconite.

Chikkim Formation: This formation unconformably overlies the Giumal Formation and is divisible into a 'Basal Limestone Member' and an 'Upper Shale Member.' The older member is made up of grey to bluish grey limestone and dolomitic limestone with alternation of shale and marl in the upper part. At the contact with the Giumal sandstone is a 20-30 cm quartzite band within two-metre thin carbonaceous shale. The 'Limestone Member' contains *Globotruncana* and radiolaria. Important faunas in this member include *Lenticulina* sp., *Dentalina* sp., *Nodosaria* sp., *Palmula rugosa*, *Lagena* sp., *Pseudotextularia* cf. *elegans*, *Rotalipora appenninica* (all foraminifera), *Belemnites* and *Inoceramus*. The limestone member is assigned a Cenomanian to Turonian age. The lithofacies and carbonate microfacies of this member is typical of shelf to outer-shelf environment. The shale member rests conformably over the limestone member. It comprises grey, ash grey, silty shale, shaly limestone, marl and fine siltstone bands. The important foraminiferal assemblage in this horizon includes *Globotruncana gansseri dicarinata, G. tricarinata, G. linneiana, Textularia* sp. and *Hedbergella* sp. This possibly represents a deposit of deep shelf. It is considered to be of Campanion to Maastrichtian age.

The Chikkim Formation represents stratigraphically the highest beds of the Tethyan sedimentary sequence in Lahaul-Spiti, though in the Zanskar segment of the larger Spiti-Zanskar basin, Palaeocene-Eocene Kanji Group follows it.

Uttarakhand

In Malla Johar area near Sancha Malla in Pithorgarh district of Uttarakhand occur Mesozoic rocks in the Kumaun Himalaya. The Lower Cretaceous rocks in Malla Johar area belong to Spiti Formation and Giumal Sandstone Formation (Table 8.6). In the section in the neighbourhood of Laptal camping ground, five ammonoid zones in the ammonoid dominated upper division of Spiti Shale Formation have been recognised and the youngest zone being assigned to Berriasian-Valanginian age. This zone contains the following fossils: *Acanthodiscus, Distoloceras, Neocomites, Bochianites* and *Neocosmoceras.*

Table 8.6. Classification of Upper Jurassic-Cretaceous rocks of Malla Johar Area, Kumaun Himalaya (after Garg et al. 1981)

Malla Johar Supergroup	Sancha Malla Group	Balcha Dhura Formation	Basic volcanic rocks, shale, Radiolarian cherts	90 m ?post-Cretaceous
		Jhangu Formation	Greywacke, shale, sandstone foram, limestone, chert	400 m Upper Cretaceous
		Giumal Sandstone Formation	Glauconite sandstone, silt radiolarians	400 m Lower Cretaceous
		Spiti Shales Formation	Shales, silts, nodules, ammonites	250 m Lower Hauterivian-Oxfordian
	Rawali-Bagar Group	Ferruginous Oolitic Formation	Ferruginous oolitic limestone with abundant ammonites	10 m Callovian

Increasing siliceous cherty bands observed towards the top of the Spiti Shale Formation are rich in radiolarians of Lower Cretaceous age. These are present in the upper part of the Jangu Formation as well as in the Balcha Dhura Formation. The radiolarian shells have undergone glauconitization.

East Coast

The East Coast Cretaceous sedimentary basins namely the Krishna-Godavari basin in the north and the Palar basin in the south are located towards the tapering ends of the crescent-shaped Cuddapah basin of Proterozoic age. The Cretaceous sedimentary outcrops located east of Cuddapah basin i.e., Guntur, Ongole and Nellore areas in Andhra Pradesh show evidence of fluvial and fluviomarine deposition. It is the reactivation of the eastern margin of the

Cuddapah basin, possibly as a consequence of break up of Gondwanaland, which led to the formation of these Cretaceous sedimentary basins. In the Palar basin of about 4000 km^2, the Lower Cretaceous marine sediments, considering their areal spread and thickness in the central and northeastern parts, were assigned a new formational status as Avadi Formation. This formation contains ammonites, belemnites, bivalves and foraminifers of Neocomian to Aptian age. The subsurface stratigraphy is presented in the Chapter on Offshore Geology.

Trichinopoly Area (Tiruchirapalli)

The great Cenomanian (98 Ma) transgression covered considerable area in the southeastern part of Tamil Nadu between the Cauvery river and Pondicherry. Ponniar and Vellar rivers separate the areal distribution into three disconnected regions, viz. Pondicherry, Vridhachalam and Ariyalur (eastern part of Trichinopoly district). They fall under Survey of India toposheet nos., 58 I/16, 58 J/13 and 58 M/4. Of these, the outcrops near Trichinopoly are the largest with an areal extent of about 400 km^2 ranging in age from Aptian/ Albian to Early Paleocene with a stratigraphic record of nearly 120-61 Ma. The sedimentation is often interrupted by low angle unconformities.

The Cretaceous succession, ever since it was mapped and studied by Blanford (1862), has been the focus of attention by many. Recent spurt of activity of hydrocarbon exploration in these areas has brought out a wealth of information on biostratigraphy, paleoenvironmental analysis and basin evolution. The latest map compiled from different sources is given as Fig.8.15.

The Cretaceous succession in the Trichinopoly area is broadly divided into three widely known groups in ascending order of superposition as Uttatur, Trichinopoly and Ariyalur and the Early Paleocene sediments as Niniyur. The Cretaceous succession in Trichinopoly area is summarised in the Table 8.7.

Stratigraphy

The Archaean crystalline gneisses and charnockites with a NE-SW trend constitute the floor for this depocentre. Small hillocks along the Perambalur-Trichinopoly road delimit the western margin. A thin fringe of Upper Gondwana sediments resting unconformably over the basement intervenes the succession as seen 1.5 km ENE of Uttatur and 1.5 km NE of Terani. The Boulder Conglomerate is a classic example for fanglomerate, derived from a tectonically active source due to faulting, in association with coalescing alluvial fans. The Terani Plant Beds, a unit of kaolinitic clay and ferruginous sand interbeds, are well known for their rich plant fossils such as *Cladophlebis indica, Actinopteris*

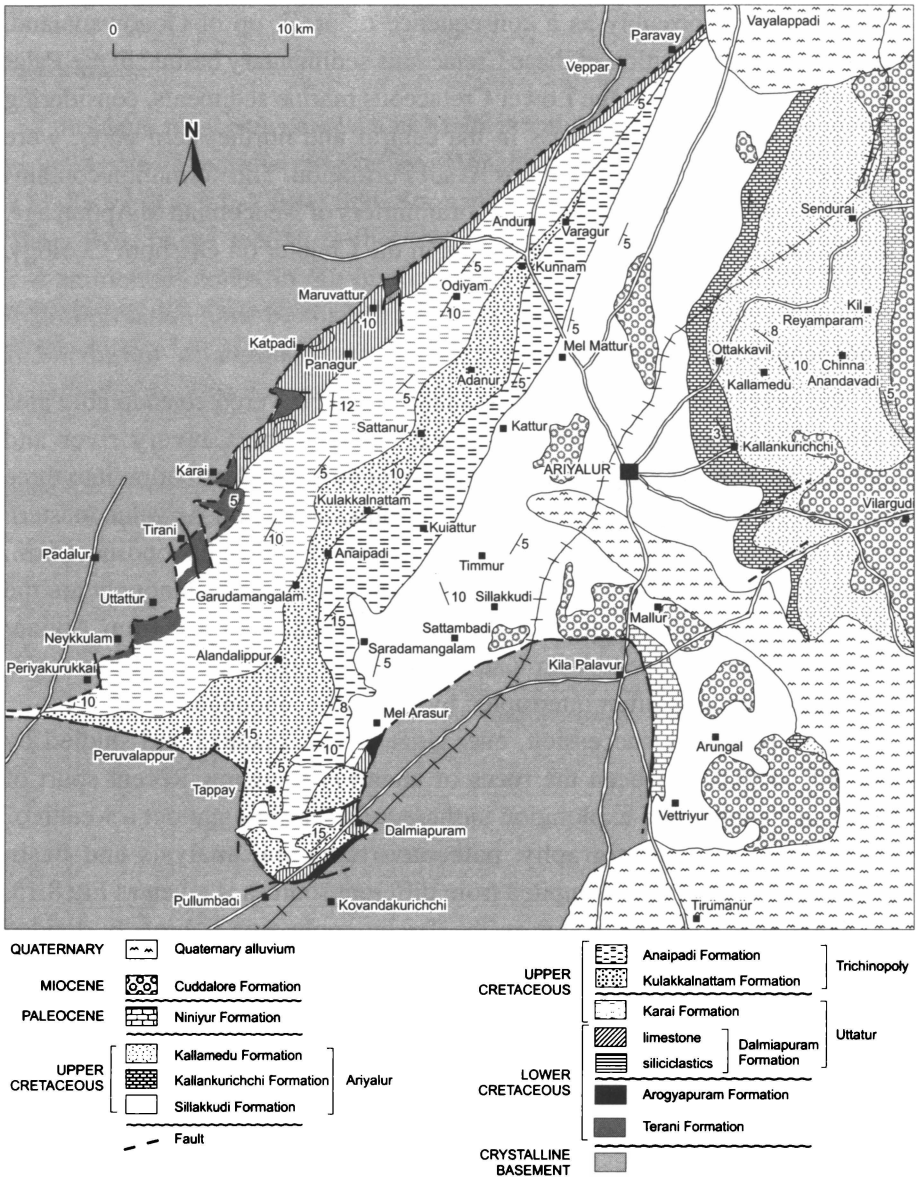


Fig.8.15. Geological map of the Ariyalur district showing the distribution of Cretaceous and Tertiary Formations (after Sundaram et al. 2001; legend modified)

(filicales), *Ptilophyllum acutifolium* (cycadophyte) and *Elatocladus conferta* (conifers). A low energy inland lacustrine environment is ascribed to this unit.

The Cretraceous sediments dip at very low angles, though higher dips have been recorded close to the contact zones of the sediments with the crystalline rocks. The sediments of the Uttatur and Trichinopoly Groups show

Table 8.7. Stratigraphy of Trichinopoly Area (after Govindan et al. 1998)

Age	Group	Formation	Lithology and Fauna
Early Paleocene	NINIYUR	Niniyur (60 m)	Limestone; *Nautilus danicus, Lyria formosa, Codakia percrassa*, Algae, Foraminifera (*Thalmannita madrugaensis, Triloculina trigonula* etc), Ostrocodes
Campanian to Maastrichitian	ARIYALUR	Kallamedu (100 m)	Sandstones and variegated clays Reptillian fossil remains, *Megalosaurus, Titanosaurus*; Dinosaur: *Bruhathakayosaum matleyi*
		Ottakovil (60 m)	Calcareous sandstones and siltstones Echinoids: *Stygmatopygus elatus* Lamellibranch: *Durania mutabilis* Ammonite: *Gunnarites kaklika, Pachydiscus otokodensis*; Ichnofossils: *Thalassinoides, Ophimorpha*, Foraminifera: *Globotruncana staurtiformis, Globotruncana arca*
		Kallankurichi (40 m)	Limestones and marls Ammonite: *Hauriceras rambda, Pachydiscus egertoni*; Lamellibranch: *Phygraca vesicularis, Exogyra tamulica, Rastellum (Arcostrea) pectinatum*; Foraminifera: *Globotruncana gansseri, Rugoglobigerina hexacamerata, Lepidorbitoides* sp., *Siderolites calcitrpoides*, Ostracods; Echinoids: *Stygmatoygus elatus*
		Sillakudi (500 m)	Sandstones with minor limestone Ammonite: *Karapadites karapadensis*, Lamellibranchs: *Inoceramus* Echinoids: *Pentacrinus*; Brachiopods: *Cretirhynchia plicatiloides, Carneithyris carnea* (Terebratulids); Foraminifera: *Bolivinoides decoratus, Globigerinelloides asperus, Kathina minuscula*
Coniacian -Santonian	TRICHINOPOLY	Anaipadi (100 m)	Sandstones, Siltstones and concretionary bodies Ammonites: *Placenticeras tamulicum*; *Kossmaticeras theoboldinum; Damesites sugota, Eubaculites otacodensis*; Bivalve: *Cardiceramus parareberti*; Gastropods: *Voysa* aff. *scalaroideum, Arcotia indica, Pseudomaura nobilis*
		Kulakkalnattam (50 m)	Limestone, sandstones, siltstones and concretions of arenaceous limestones Bivalve: *Physa, Trigonia*; Ammonites: *Nautilus, Mespuzosia indopacificum, Placenticeras tamulicum, Kosmaticeras recurrens, Lewesiceras vaju, Allocovioceras* sp., Gastropods: *Gyrodes tenellus, Crytorhytis attenuata* Brachiopods: *Cretirhynchia plicatiloides, Terebratulids*
Upper Albian - Middle Turonian	UTTATUR	Karai Shale (400 m) Maravattur Clay (400 m)	Ammonite: *Mammites cancellatum, Eucalycoceras pentagonum, Calycoceras neuboldi, Schloenbachia inflata, Scaphites kingeanus, Turrilites costatus*; Lamellibranchs: *Pecten, Alectryonia; Serpulids, Crinoid spines, Belemnite guards;* Foraminifera: *Lenticulina kossmatina, Rotalipora cushmani, Marginotruncana indica, Helvetoglobotruncana helvetica, Planomalina buxtorfi*, Ostracodes, Nannofossils: *Chiastozygus litterarius, Microrhabdulus decoratus, Quadrum qartneri*;
Middle Aptian - Middle Albian		Kallakkudi limestone (Dalmiapuram) (75 m)	Lamellibranch: *Pecten, Oysters*, Rudistt: *Sphaerulites indica* Echinoids: *Cidaris*, Serpulids; Foraminifera: *Lenticulina macrodisca, Hedbergella planispira*; Sponges: *Lithistida pharetronids, Calzichondrilla crustans;* Corals: *Microsolena, Eugyridae*; Algae: *Ethelia alba, Acecularia, Halimeda, Solenoporacea, Pyctonoporidium*;
		Grey shale (50 m)	Dark grey shale, Pyrites, Woody remains
		Boudler Conglomerate (5 m)	
	Upper Gondwana	Terani plant beds (30 m)	*Ptilophyllum acutifolium, Elatocladus conferta*
Archaean		Crystallines	

evidences of folding. The faults traced at the western boundary of the Cretaceous sediments are thought to be reactivated Precambrian faults. In the latest study (Sundaram et al. 2001), an attempt has been made to infer sedimentation rate, relative sea levels and transgression cycles in the Cretaceous succession in the Ariyalur district based on the study of 2325 m mid-Cretaceous-Paleocene sequence, over an interval of about 35 Ma. The mean rate of sedimentation is estimated to have varied between 15 and 240 mm per thousand years. The provenance for these sediments was the Archaean crystalline rocks to its west, and from the nature of the sediments, predominance of physical weathering is suggested.

These sediments abound in a variety of invertebrates and a few vertebrates. Among the invertebrates, the most noteworthy are the ammonites, followed by bivalves, gastropods, echinoids, foraminifera, bryozoa etc. Important fossils reported from some of the formations are given in Table 8.7.

Uttatur Group

Basal conglomerates, grey shales, sponge-coral-algal limestone and shale/clay distinguish this group, resting unconformably over the basement with phosphatic nodules having a maximum thickness of about 600 m.

The Grey Shale, occurring below the Kallakudi Limestone, appears to be an extensive unit and it has been logged in the subsurface in different parts of the Cauvery basin and identified as primary source for generating the hydrocarbon.

The Kallakudi/(Dalmiapuram) Limestone, which is actively mined for cement, is a sponge coral-algal reefal limestone. It is composed essentially of different siliceous and calcareous sponges, layered corals, algae, bivalves, cidarids, belemnites, bryozoans, foraminifera and coral fragments. Sponges are sessile organisms, which occur as both flat, crust like type, mostly siliceous and occurring as colonies. Though partly dissolved by diagenesis, skeletons/frames are preserved. The age of this unit is Middle Aptian-Middle Albian. The limestone is presumably deposited in an intertidal zone in a protected still-water bay.

Karai Shale/clay is dominantly dark grey, chocolate brown to yellow (Maravattur Clay- a facies equivalent to Karai Shale) with occasional ferruginous sands and limestones. These are splintery in nature and contain veins of gypsum, celestite, phosphate nodules (all evaporites) and abundant belemnite guards. The fossils present include ammonites, serpulid worms, bivalves (*Pecten*, *Alectryonia*, *Exogyra*), foraminiferids, nannofossils, and ostracodes. This unit is assigned to Late Albian to Middle Turonian age. The topography is characterised by trellis type drainage and exhibits badland topography.

Trichinopoly Group

The group unconformably rests over the Uttatur, and it is well evident at places. It is divisible into lower Kulakkalnattam (=Paravay) and upper Anaipadi (=Garudamangalam) Formations separated from each other by a conglomerate bed. Kulakkalnattam Formation is a calcareous sandstone unit with ferruginous concretionary bodies extensively bioturbated by feeding burrows like *Thalassinoides.* It is intercalated with dark grey limestone containing thick-shelled bivalves (Oysters), ammonites, rhynconellids, brachiopods and silicified wood. The thickness of this unit is about 60 m.

The succeeding unconformably overlying Anaipadi Formation is essentially made of sandstones, siltstones with concretionary layers rich in fossils. The fossils recorded include inoceramids, gastropods, and ammonites besides large fossil tree trunks bored by wood-boring teridinids. An 18 m long conifer fossil tree is preserved as a geological monument at Sattanur. It is of Coniacian-Santonian age. Partial skull, tooth, sacrum, pelvic elements, armour plates of *Stegosaurus* dinosaur were picked up near Siranattam. The thickness of this group is about 100 m. A regressive coastal environment is suggested for the sediments of this group.

Ariyalur Group

It lies unconformably over the Trichinopoly Group and consists of two dominantly sandstone bodies separated by limestone. The lower Sillakudi Formation comprises ferruginised arkosic sandstone and limestone bands. The fossils recorded include large sized *Nautilus*, *Inoceramus*, rhynconellids, echinoids, ammonites and foraminifera. The group is assigned to Campanian. The depositional environment appears to be high-energy transgressive tidal bars or shoals.

The Kallankurichi Formation, resting unconformably over the Sillakudi Formation, is a massive rudist bivalve carbonate shell-bank of about 40 m thickness. It is mined for cement industry. Lithologically it is mainly made of bioclastic packstone, grainstone facies. The fossils recorded include bryozoans, rudist bivalves (*Gryphea*, *Alectryonia*, *Lopha*) brachiopods, echinoids, ammonites, foraminifera (*Lepidorbitoides* and *Siderolites*) and ostracodes. The age of this unit is Upper Campanian-Early Maastrichtian. This carbonate unit is considered to be a shallow marine carbonate bank/shoal deposit.

The overlying calcareous sandstone, of about 60 m thickness, mapped as Ottakovil Formation, contains fossils of echinoids (*Stygmatopygus elatus*), *Alectryonia*, *Eubaculites*, turritellids, bryozoans and ichnofossils like *Thalassinoides* and *Ophimorpha.* The age is Maastrichtian. The lithology and

faunal remains are suggestive of marginal marine to near shore condition of deposition.

Ottakovil Formation is overlain by white to grey, cross-bedded thick sandstones intercalated with greenish grey to red clays, which delimit the Cretaceous succession. It is widely known as Kallamedu Formation in which the presence of reptilian fossils such as bones of *Megalosaurus, Titanosaurus* and remains of herbivorous dinosaurs *Bruhathakayosaurus matleyi* of Maastrichtian age have been reported. The presence of vertebrate fossils, good textural maturity of sandstones, and cross bedding in sediments indicate shallow fluvial channel deposition with variegated clays as over-bank deposits. The Ariyalur sediments occur in other areas in Vridhachalam and Pondicherry. A deep exploratory well drilled by ONGC near Ariyalur has penetrated about 620 m of Ariyalur, 300 m of Trichinopoly and 1750 m of Uttatur Groups before entering the basement at 2670 m.

Niniyur Formation

The Cretaceous succession is unconformably overlain by a thick carbonate sequence extending from Vellar river in the north to Kavanur in the south over a strike length of 26 km as disconnected outcrops. The carbonate sequence is of about 60 m in thickness. Lithologically this unit is divisible into lower fossiliferous limestone, middle recrystallised shelly limestone and upper argillaceous gritty nodular limestone collectively known as Niniyur Formation. These carbonate beds too, are presently mined for cement industry. The fossils present include algae, cephalopods *(Nautilus danicus)*, gastropods *(Nerinea)*, foraminifera and ostracodes suggesting an early Paleocene age. Beds equivalent to Niniyur Formation are seen in Vridhachalam and Pondicherry areas, as well.

Biochronostratigraphic boundary markers of Cretaceous for Indian stages, based on the first and last appearance datum (FAD & LAD) of certain foraminifera collected from the subsurface samples in the Cauvery offshore basin, are given in Fig.12.2.

Narmada Basin

Bagh Beds: These sediments occur as detached outcrops along the north bank of Narmada river, traceable from Barwah in Khargone district of Madhya Pradesh in the east to Chhota Udaipur in Baroda district and Rajpipla in Broach district of Gujarat, in the west (Fig. 8.16). They rarely attain a thickness of more than 40 m over much of their extent, attaining perhaps 300 m in Amba Dongar area, and to the south of Narmada around the valley of Deva river, a

tributary of Narmada. The stratigraphic succession based on Chiplonkar's studies is presented in Table 8.8 comparing with an earlier succession of Bose.

Sedimentation: Starting with deltaic environment of lower part of Nimar Sandstone, the deposition of its upper part and the limestones and the marls, which follow, was under a series of marine transgressive and regressive phases with their relevant faunal assemblages. Marine history of Narmada basin ended with oyster bed at the top of Upper Coralline Limestone Bed, with westward retreat of the sea, and freshwater conditions progressively overstepping westward with the deposition of the Lameta Beds.

The first sign of marine invasion of the Narmada valley may be in Amba Dongar area seen in the form of trace fossil horizon yielding a rich ichnofauna. This is followed by oyster bed and *Astarte-Turritella* bed. In some localities (for example, in Deva river valley, south bank tributary of Narmada) presence of appreciable amounts of pyrites shows oxygen-poor conditions which being unsuited to life is indicated by the absence or rarity of fossils. Bagh ammonoids belonging to the *Tennuous involute* Group range over 20 to 150 fathoms. Thick-shelled bivalves and gastropods, bryozoans and serpulids all taken together indicate clear, warm, tropical marine waters for the Bagh fauna. Abundance of echinoids in all the limestones and the marl and of bryozoans and algae, particularly in Coralline Limestone, shows that these beds must have been deposited in clear, well-aerated and euphotic (part of the ocean in which there is sufficient light to support photosynthesis) conditions. Several hard grounds with extensive evidences for submarine and subaerial erosion have been recorded in the Bagh carbonate sequence. These surfaces denote the relative fall in sea level intervening the period of sea level rise.

Life: Bagh Beds is a single palaeontological unit in spite of lithological differences in the constituent members of the group, and contain the following fossils:

Ammonoidea:	*Placenticeras mintoi, Namodoceras scindia, N. bosai Coilopoceras, Parastantanoceras, Proplacenticeras*
Bivalves:	*Astarte, Inoceramus, Birostrina, Cataceramus, Cremnoceramus, Mytiloides, Sphenoceramus*
Gastropoda:	*Turritella, Tylostoma globosum, Ampulina bulbiformis*
Echinoidea:	*Hemiaster* is the most conspicuous, *Tetragramma*

Most of the above range in age from Cenomanian to Santonian.

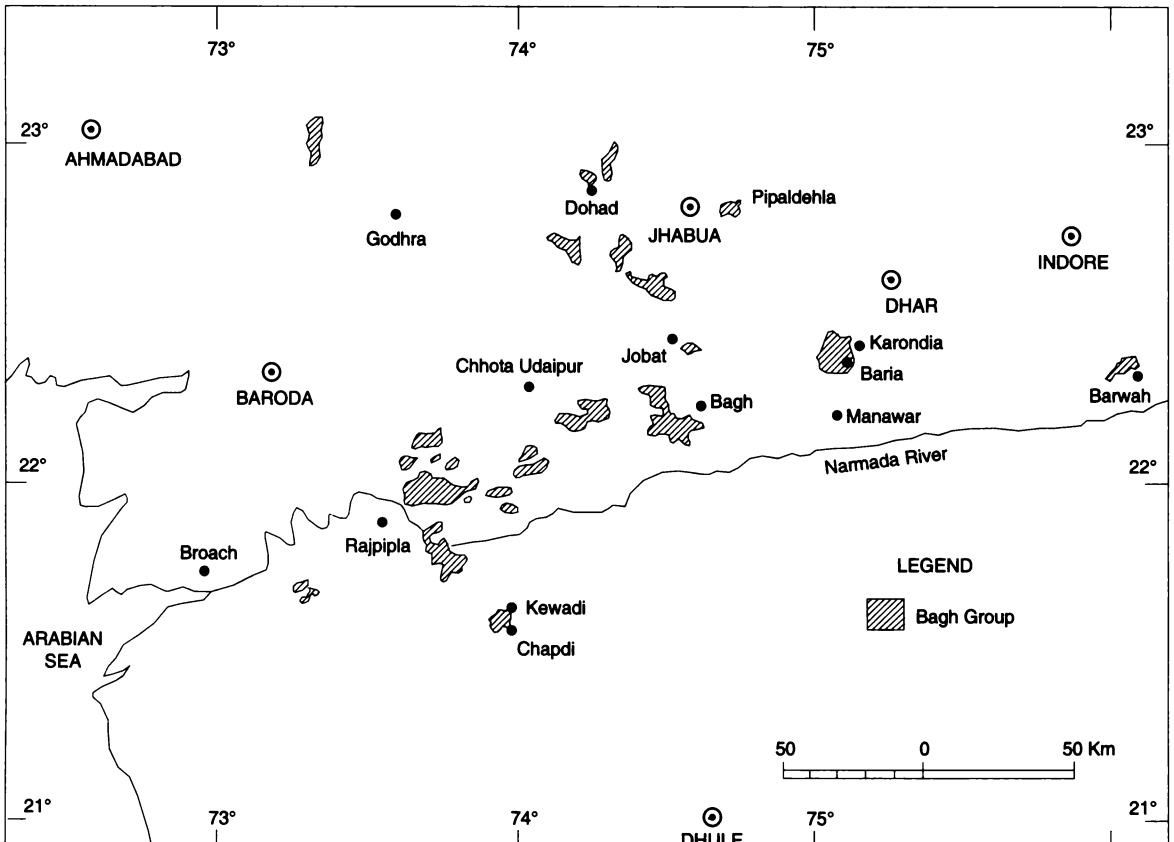


Fig.8.16. Outcrops of Bagh Group along Narmada river valley. (after Kundal and Sanganwar, 2000)

Table 8.8. Stratigraphy of Bagh Formation (source: Merh, 1995, p.64; modified)

Geological Time Scale	Bose (1884)	Chiplonkar, Badve and Ghare (1972, 1974)
Paleocene		
Maastrichtian		
Campanian	SENONIAN Coralline Limestone	Lameta
Santonian		
Coniacian		Upper coralline limestone with oyster bed at the top
		Upper *Inoceramus* bed
Turonian	Deola and Chirakhan Marl	Deola and Chirakhan Marl with *Hemiaster*
		Lower Coralline Limestone
		Lower *Inoceramus* bed; nodular limestone
Cenomanian		*Astarte - Turritella* bed
Albian	Nodular Limestone	
Aptian		Oyster bed with shark teeth
Barremian	NEOCOMIAN Nimar Sandstone with oyster bed at the top	Trace fossils horizon, Lower portion of Nimar Sandstone
Hauterivian		
Valanginian		

The calcareous algal assemblage belonging to Cyanophyta, Rhodophyta and Chlorophyta at the top of the Nimar Sandstone is considered to have been deposited in tropical waters at a depth of 10-12 m from below low tide level, in a moderate energy setting with moderate turbulence and normal salinity of water. They point to a Cenomanian-Turonian age and some of the species are common to Indo-Mediterranean region. Nautiloids, acanthoceratids, desmoceratids, phylloceratids and belemnoides as also heteromorphs like *Baculites, Turrilites, Anisoceras* etc. are totally absent in Narmada valley, so also pycnodonts, rudistids as also Terebratulid brachiopods. 'Bagh Beds' have distinct Mediterranean faunal affinities and there was no direct connection between the Narmada basin and the Cauvery basin.

Shark teeth have been collected from Amba Dongar (in Oyster Bed,

Nodular Limestone and Coralline Limestone). They belong to the following species:

Scapanorhynchus baghensis; Lamma mongraensis
Ginglymostoma sokotense; Prinodon ambadongerensis

The Bagh Beds in the eastern part of the Narmada basin has been pervasively remagnetised by the igneous activity of Deccan Trap. This overprinted palaeomagnetic signature in the Bagh Group indicates a counter clockwise rotation by 13°±3° and a latitudinal drift northwards by 3°±3° of Indian subcontinent during volcanism.

Lameta Formation

Lameta Formation has attracted the attention of geologists partly because of (i) association with infra- and inter-trappean sediments, (ii) importance for Cretaceous-Tertiary boundary and (iii) dinosaur skeletal remains found for the last 150 years. Upper Cretaceous Lameta Formation is exposed as horizontal shelves along some fringe areas of the Deccan Trap in Peninsular India. It occupies more than 5000 km^2 as detached outcrops in parts of Central and Western India. The depositional areas can be categorised as belonging to the following geographical basins (Fig.8.17): (i) westernmost Balasinor-Jhabua basin; (ii) Jabalpur basin; (iii) Sagar basin; (iv) easternmost Ambikapur-Amarkantak basin; (v) southernmost Nand-Dongargaon basin. The type area of Lameta (23°6'54"N: 79°50'15"E) is situated on the right bank of Narmada river, about 15 km southeast of Jabalpur city (*see* pp.779-780).

Lithostratigraphic succession of Lameta rocks in Narmada basin along with those of the younger and older formations is given in Table 8.9.

Environments of deposition: The basal Green Sandstone is interpreted as a braided stream deposit (*see* Table 8.9 for the sequences). The Lower Limestone, characterised by brecciation and shrinkage cracks is interpreted as a sub-aerially exposed palustrine flat with calcrete formation on topographic highs of low relief plains. The overlying Mottled nodular beds exhibit a variable range of calcrete fabrics and morphologies including circum-granular and linear cracks, root casts and nodules. These are interpreted as pedogenically modified sheetwash deposits of a semiarid alluvial plain. The Upper Calcareous Sandstone is a sheet flood deposit, again pedogenically modified before arrival of the basal lava flows.

Fauna and Flora: A diverse assemblage of aquatic and semi-aquatic and terrestrial fauna and flora, including *in situ*, near-complete fish remains, has

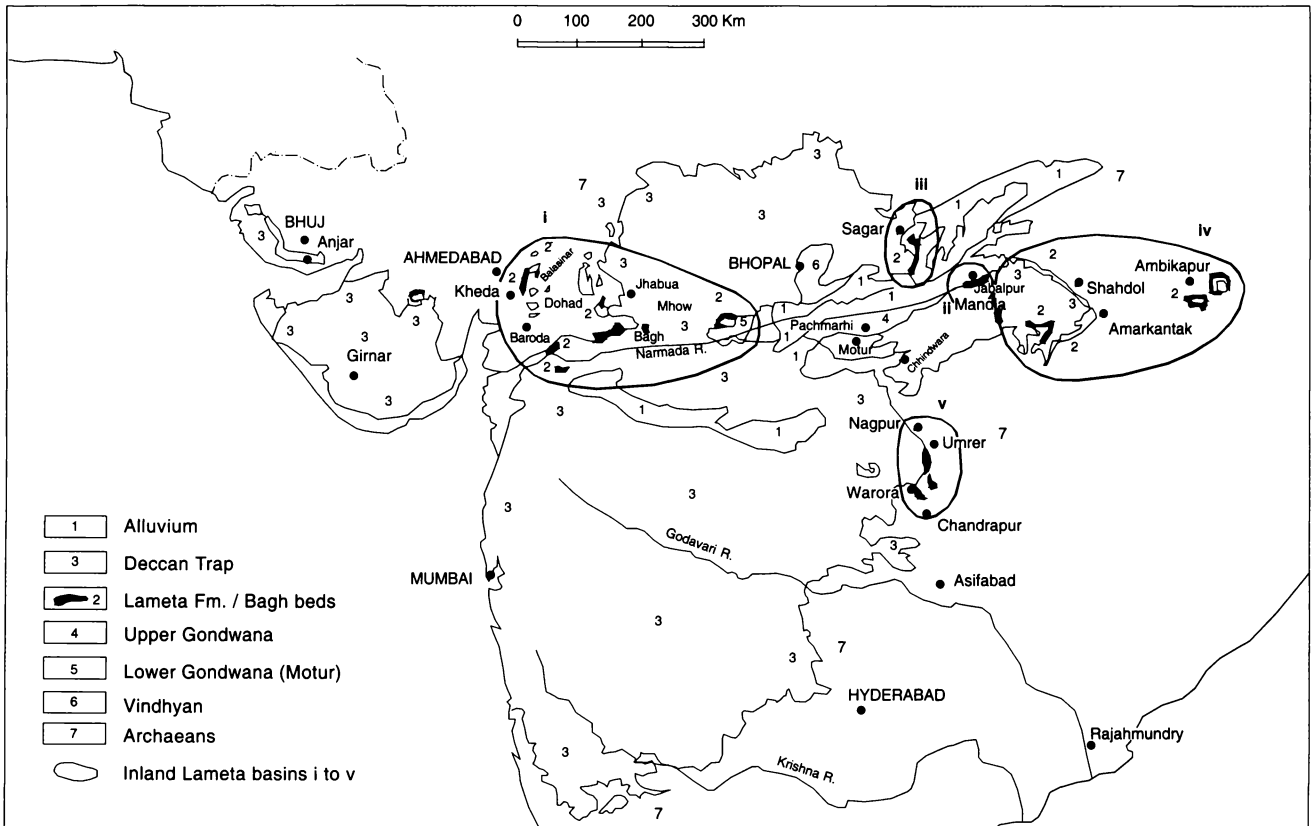


Fig.8.17. Map showing different inferred basins of Lameta sedimenataion (after Mohabey and Udhoji, 2000). (**i**) Balasinor-Jabua; (**ii**) Jabalpur; (**iii**) Sagar; (**iv**) Ambikapur-Amarkantak; (**v**) Nand-Donargaon.

Table 8.9. Lithostratigraphic succession of Lameta rocks in Narmada basin (after Joshi and Ganapathi, 2000)

Age	Formation	GUJARAT Lithology	GUJARAT Fossils	BAGH Lithology	BAGH Fossils	JABALPUR Lithology	JABALPUR Fossils
Recent and Sub-recent		Black cotton soil and alluvium	-	Black cotton soil and alluvium	-	Black cotton soil and alluvium	-
		(Erosional unconformity)					
Late Cretaceous to Early Palaeocene	Deccan Trap	Variety of basalts with intertrappean limestones	Fresh water molluscan remains	Variety of basalts dykes	-	Variety of basalts with intertrappean limestones	Molluscan and vertebrate remains
		(Eruptive unconformity)					
Maastrichtian	Lameta Formation	Cherty limestones (3-12 m)	Complete and broken egg shells, teeth of dinosaurs Angiosperm seeds and ostracods	Cherty limestones (3 m)	Complete eggs, foot-print and bones of dinosaur	Upper calcareous sandstones (5 m)	
						Upper limestones (5 m)	Dinosaur eggs and bones
		Sandstones (0.5-1.5 m)	Fossil bones and footprints of dinosaur	Calcareous sand-stones (1.5 m)	-	Mottled nodular bed (10 m)	Dinosaur eggs Bivalves
		Conglomerate (0.5-2 m)		Redstones (2 m)	-	Lower limestones (3.5 m)	Dinosaur eggs and bones
						Green sandstone (4.5 m)	Dinosaur bones
		(Erosional unconformity)					
Cenomanian to Turonian	Bagh Formation	HIATUS	Sandstones	Marls, shales, shells and conglomerates	Molluscs Shells oysters	HIATUS	
		(Erosional unconformity)					
Jura-Cretaceous	Jabalpur Group	HIATUS		HIATUS	Clays and sandstones		
		(Erosional unconformity)					
	Erinpura Granite	Granites		Not Exposed	Not Exposed		
		(Intrusive contact)					
	Aravalli Supergroup/ Bijawar Group	Quartzites, Schists Phyllites, Amphibolites		Quartzites Phyllites Gneisses			

been unearthed from Lameta Formation (Table 8.10). Almost all the vertebrate and invertebrate taxa known from the inter-trappean sediments became known for the first time from the Lameta sediments that provided well-preserved material for reliable taxonomic identification. Similarly their *in situ* mode of preservation has provided better parameter for the palaeoecological and palaeoenvironmental interpretation (*see* Jabalpur, pp.779-780).

Dinosaur eggshells: The first *in situ* dinosaur nest with eggs was found by Mohabey in the year 1981 from a limestone (calcreted sandstone) bed of the Lameta Formation in a quarry section at Balasinor in the Kheda district of Gujarat and also from Madhya Pradesh and Maharashtra. The eggs occur as (i) nests of whole and partly preserved eggs in the nesting site, (ii) isolated nests, (iii) stray rolled eggs and (iv) eggshell debris. The eggs usually occur in a single layer in a saucer shaped pit. The dinosaurs always preferred to lay their eggs in the soft sand of the riverbanks.

Five eggshell types (attributed mostly to titanosaurid sauropods) have been recognised based on morphological characters. The most important and well-studied localities of nesting sites in the region are Anjar (Kutch), Balasinor (Kheda), Dohad, Hathni river (near Kukshi) and Bagh caves, Jabalpur, Pisdura and Nand, Nagpur (Takli).

Coprolites (fossilized fecal material): Pisdura in Warora district, Chchindwara (Maharashtra), and Madla (Madhya Pradesh) are excellent localities of dinosaur coprolites in India. The former constitutes one of the largest coprolite deposit at a single site in the world. Here the coprolites are associated with sauropod skeletal elements and have yielded wood, leaves and seeds etc. The carnivorous dinosaur coprolites have yielded residues of bone, teeth, fish scales, mollusks etc.

Analysis of the depositional environments of the strata of Bagh, Lameta and infra-trappeans of Lower Cretaceous in Central India reveal that an epicontinental seaway advanced from the west during the Turonian (?) and inundated areas a few hundred kilometres inland of the Lower Narmada basin. Earlier phases of rift-related sedimentation included estuarine facies (Nimar Group) in the Lower Narmada basin and fluvial channel facies (Jabalpur Group) in the upper part of the basin. Fluvial/lacustrine/palustrine (marshy) and sheetwash deposits constitute the infra- and inter-trappean sequences (the latter in the Deccan Trap), which are broadly coeval with the Maastrichtian Deccan lava flows.

Age: Based on vertebrates (especially the Piscean fauna) evidences, the Lameta sediments are indicated to have a concurrent stratigraphic age as Maastrichtian. The faunal and floral evidences from the Lameta Formation

Table 8.10. Biota of Infra-trappean (=Lameta) beds (pers. commn. G.V. R. Prasad)

	Andhra Pradesh		Gujarat	Madhya Pradesh	Maharashtra		
	Marepalli	Rajah-mundry	Rahioli	Jabalpur	Dongar-gaon	Pisdura	Umrer
Gastropods:							
Lymnaea oviformes					x		
Lymnaea subulata				x			
Melania hunteri					x		
Physa bridgerensis					x		
Physa inflata					x		
Physa longiscula					x		
Physa prinsepii	x			x	x		
Planorbis sp.				x			
Paludina deccanesis					x		
Paludina hislopi				x	x		
Paludina normalis				x			
Paludina pyramis				x			
Bivalves							
Unio deccanensis					x		
Corbicula sp.					x		
Ostracodes:							
Altanicypris bhatiai				x			
Candona sp.					x		
Candona altanulaensis				x			
Candona cf. *C. hubeiensis*				x			
Candoniella sp.					x		
Cyclocypris transitoria					x	x	
Cypria elata					x		
Cypridea sp.				x	x	x	
Cypridopsis sp.					x		
Cytheridella strangulata					x	x	
? Cypridopsis bugintsavicus				x			
Darwinula sp.				x	x		
Eucypris cf. *E. bajshintsavica*				x			
Frambocythere tumiensis tumiensis				x			
Mongolianella sp.					x		
Mongolianella khamariniensis			x				
M. palmosa				x			
Mongolocypris cf. M. gigantea			x				
Paracandona jabalpurensis				x			
Paracypretta jonesi					x	x	
Trapezoidella sp.						x	
Foraminifers:							
Cibicides mensilla		x					
Guttulina lactea		x					
Planulina bhatiai		x					
Pseudopolymorphina devarapalleensis	x						
Quinqueloculina sp.		x					
Vaginulina cf. *V. cenomana*		x					
Charophytes:							
Amblyochara concava					x	x	
Microchara grambasti					x		
Nemegtichara grambasti					x		

Table 8.10. Contd....

	Andhra Pradesh		Gujarat	Madhya Pradesh	Maharashtra		
	Marepalli	Rajah-mundry	Rahioli	Jabalpur	Dongar-gaon	Pisdura	Umrer
Microchara grambasti					x		
Nemegtichara grambasti					x		
Platychara compressa					x		
Platychara perlata					x	x	
Platychara rajahmundrica					x		
Platychara raoi NN					x		
Peckichara disermas					x		
Peckichara varians					x		
Nemegtichara grambasti					x		
Stephanochara sp.					x		
					x	x	
Pollens and Spores:							
Ariadnaesporites punctatus				x			
Aquilapollenities andamanensis			x				
Aquilapollenites bengalensis				x			
Aquilapollenites indicus				x			
Callialasporites				x			
Callialasporites trilobatus					x		
Cycadopites couperi				x			
Lametaea indica				x			
Leptolepidites verrucatus				x			
Liliacidites microreticulatus				x			
Proxapertites crassimurus				x			
Palmaepollenites sp.				x			
Palmidites maximus					x		
Palmidites plicatus				x			
Polyadopollenites mesozoicus				x			
Scollardia conferta				x			
Tricolpollenites				x			
Trilobosporites					x		
Fishes:							
Selachii:							
Myliobatiformes							
Igdabatis indicus	x						
Rhombodus sp.	x			x			
Lepisosteiformes							
Lepisosteus indicus	x			x	x		
Seminotiformes							
Lepidotes sp.					x		
Holosteii: -							
Pycnodontiformes							
Pycnodontidae gen. et sp.indet.			x				
Pycnodus lametae	x			x			
Teleostei:							
Aulopiformes							
Enchodus					x		
Clupeiformes							
Clupea DG					x		
Osteoglossiformes							
Phareodus sp.	x			x	x		

Table 8.10. Contd.....

	Andhra Pradesh		Gujarat	Madhya Pradesh	Maharashtra		
	Marepalli	Rajah-mundry	Rahioli	Jabalpur	Dongar-gaon	Pisdura	Umrer
Perciformes							
Eoserranus hislopi					x		
Nandidae indet.	x					x	
Amphibins:							
Anura indet.	x						
Reptiles:							
Chelonia (Turtles):							
Chelonia indet.	x				x		
Shweboemys pisdurensis					x	x	
Squamata (Lizards):							
Lacertilia indet.	x				x		
Crocodilia:							
Crocodilia indet.		x			x	x	
Dryosauridae indet.		x					
Dinosaurs:							
Saurischia:							
Sauropoda:							
Jainosaurus septentrionalis			x	x	x		
cf. *Jainosaurus* sp.						x	
cf. *Titanosaurus indicus*						x	
Laplatosaurus madagascariensis			x	x			
Titanosaurus blanfordi				x	x		
Isisaurus colberti			x	x	x		
Abelisaurid:							
Indosaurus matleyi				x			
Indosuchus raptorius				x			
Rajasaurus narmadensis			x				
Coelurosauria: -							
Coeluroides largus				x			
Compsosuchus solus				x			
Dryptosauroides grandis				x			
Jubbulpuria tenuis				x			
Laevisuchus indicus				x			
Ornithomimoides mobilis				x			
Titanosaurid oospecies							
Ellipsoolithus khedaensis			x				
Megaloolithus baghensis						x	
Megaloolithus cylindricus				x			
Megaloolithus dholiyaensis			x				
Megaloolithus jabalpurensis				x			
Megaloolithus mohabeyi				x			
Megaloolithus padiyalensis			x				
Megaloolithus walpurensis			x				
Ornithischia:							
Stegosauria:							
Lametasaurus indicus				x			
Ornithoid oospecies							
Subtiliolithus kachchhensis			x				
Coprolites						x	x
Dinosaur's nesting sites			x	x	x		
Dinosaur's egg shells			x	x	x	x	

and the overlying inter-trappean sediments suggest that a majority of the Lameta taxa (mostly aquatic) survived the hostile environment caused by the Deccan volcanism and probably only a few could survive by migrating to safer areas away from the eruption centres. Tuffaceous or volcanic rocks of epiclastic origin have been reported from the Lameta beds around Jabalpur and Nagpur.

Lameta and coeval formations of Peninsular India are younger (Maastrichtian) than ages previously assigned to them (Cenomanian-Turonian). Major part of the Deccan basalt eruption took place during the reversed magnetic chron, 29R, which encompasses the Cretaceous/Tertiary (K/T) boundary. Radiometric dates (K/Ar, $^{40}Ar/^{39}Ar$) tend to cluster in a 60-70 Ma interval. No instantaneous mass extinction is envisaged. The Deccan Trap activity is considered to have had a short duration of about 5 Ma. Analysis of the micro vertebrates of the infra- and inter-trappean sequences shows that the biotic assemblages of the two are indistinguishable.

Latest palaeontological evidence based on dinosaur fauna and fish fauna – *Igdabatis, Rhombodus, Apateodus* and *Stephanodus* indicate – Maastrichtian, so also the palynological assemblage of *Ariadnaesporites, Leptolepidites, Proxaperites, Palmidites,* and *Liliacidites* etc. Overall the Lameta beds are considered to represent a regionally extensive Maastrichtian regolith.

According to some, the Nimar, Bagh and Lameta Beds can be accorded facies status and they cannot be regarded as time-stratigraphic units in their present form which implies that Nimar unit is somewhat older than the Bagh, and Bagh is older than the Lameta.

Jharkhand

During the Cretaceous period the East Gondwana has witnessed two prominent volcanic episodes, one in the Early Cretaceous (Rajmahal-Bengal, Sylhet volcanism at 115-118 Ma) and the other in Late Cretaceous period (Deccan volcanism at 60.2-66.5 Ma). There were other volcanic provinces during this time in other parts of the world as well. The Sylhet volcanism could be polycentred, coeval, extending between Sylhet and Rajmahal, like that of Satpura-Narmada-Tapti province of Deccan volcanism. Moreover in the Cretaceous stratigraphic sequence of Bangladesh (south of Meghalaya) volcanic tuff and conglomerates are recorded at many levels.

Rajmahal Volcanics: These rocks overlie Dubrajpur Formation (Upper Triassic to Lower Jurassic) and in places overstep on to the Barakar Formation (Permian) and Precambrian basement (Fig. 7.8). These basalts are known to continue towards east and south – Bengal basin and Mahanadi basin. The Rajmahal Trap in the eastern part of India extends over an area of about

4300 km^2. The eruption took place in a sub-aerial environment. In the Rajmahal hills basaltic lava formed more than 95% of the total exposure and the western margin, the basalts unconformably overlie the rocks of the Gondwana Supergroup. The Rajmahal basalts indicate an age of around 116 Ma.

The lava flows show gentle dips towards the east and north, following the basement topography at the time of eruption. There are at least 15 flows above the ground and 28 flows beneath it (data from borehole). Numerous bentonitic deposits, occurring mostly as pockets or thin beds, have been noted in the northeastern and central sectors of the basalt outcrop, signifying that minor explosive volcanic activity centred on these regions. The presence of current bedding, mud cracks and large boulders of the basement rocks in the inter-trappean beds east of Bagmara suggest that the basin in which they were deposited was shallow.

Rajmahal basalts generally range from quartz-tholeiitic basalt to dacite and pitchstone. The flows vary in thickness from <1 to ~70 m. Significant volcanic features observed include vent sites, marked by volcanic breccia, welded agglomerate, tuff and lapilli-tuff (including volcanic bombs). Alkali-basalts and olivine tholeiites have been intercepted in some boreholes in the Bengal Basin.

Some of the characteristics of the sediments found interbedded within the lavas suggest a humid, sub-tropical lacustrine depositional environment during the eruption of the lower part of the volcanic sequence, and a temperate climate during emplacement of the upper flows. Most of the eruptions took place through fissures sited at the faulted margin of the Indian shield (Ninety East Ridge). This magmatic activity is interpreted as resulting from extension of the lithosphere above the Kerguelan mantle plume.

The infra-trappean sequence representing Dubrajpur Formation includes kaolinite sandstone, coarse-grained ferruginous sandstone and grey and chocolate shale. The inter-trappean beds contain buff, chocolate and green coloured shales, clays and sandstones.

Flora: The inter-trappeans in the western part of the hills (representing the earliest flows) are characterised by the presence of *Ptilophyllum* and *Thinnfeldia*. These plant fossils indicate that humid subtropical climate prevailed in the Early Cretaceous. In contrast, the floral assemblage associated with the stratigraphically highest inter-trappean bed consists of *Taeniopteris spatulata, Brachyphyllum rhombicum* and *Ptilophyllum tennerrimum*. These beds are identified only in the southern part of the Rajmahal hills and are considered to be of Early Cretaceous in age. The presence of conifers in this assemblage is suggestive of a somewhat temperate climate and moderately high altitude.

Angiospermous pollen make their first appearance in the first inter-trappean bed. They are associated with the typical Lower Cretaceous palynoassemblage of reticulate monosulcate and colpoidate angiospermous pollen. These have been picked up from cores taken from a borehole No.RJNE-32, drilled near Mirza Chowki from the inter-trappean beds. A detailed study of the pollen recovered from a borehole PGD-6 in Dumra sub-basin in West Bengal, led to the recognition of three distinct palynological assemblages, belonging to the infra- and inter-trappean Mesozoic succession as shown below:

Lundbladispora – Verrucosisporites - Late Early Triassic
Murospora florida – Late Jurassic: Kimmeridgian-Tithonian
Cicatricosisporites australiensis –Early Cretaceous: Tithonian-Berriasian

The other palynomorphs from the upper part of the inter-trappeans in the Rajmahal are the following:

Polycingulatisporites crenulatus, Foraminisporis tribulisus, Contgnisporites cooksonii, Microcachryidites antarcticus

This assemblage is equated with the *Foraminisporis wonthaggiensis* palynozone of Australia and dated as Valanginian to Hauterivian (Lower Cretaceous).

Age: Early Cretaceous age (100-105 Ma) has been assigned to Rajmahal Trap on the basis of palaeomagnetic data. A recent $^{40}Ar/^{39}Ar$ dating of Rajmahal Trap indicated that its age ranges from 118-116 Ma, which places the basalt flow within the Cretaceous.

Assam/Meghalaya

In the Borghat-Narpuh section near the southern edge of Shillong Plateau the following succession is observed of the Cretaceous Mahadek Formation:

Lithology	Age	Thickness
Softer sandstone Very hard massive sandstone Boulder conglomerates (Time transgressive)	Upper Cretaceous (Maastrichtian) 65 to 74 Ma	30 m (thicker in Therriaghat 200 m)
	Unconformity	
Sylhet Trap	Early to Middle Cretaceous (110 to 133 Ma)	
	Unconformity	
Metamorphics	Precambrian	

The presence of *Gumbelina, Globotruncana, Orbitoides*, and *Siderolites* in calcareous bands near the top of the Mahadek Formation indicates Maastrichtian age.

Sylhet Trap: In Meghalaya these volcanic rocks are predominantly quartz tholeiites. Two groups of basaltic rocks were identified based on major, and REE composition. Their geochemical differences could be related to either inhomogeneities in the subcontinental lithospheric mantle source or the structure of the plume head coupled with differences in the nature and extent of fractional crystallization processes. It is believed that the Kerguelen hot spot track of the Indian Ocean links Rajmahal and Sylhet Traps with the northern part of the Ninety East Ridge.

If the Sylhet Trap poured out over a period of 23 Ma (110 to 133 Ma) it is quite possible that all the flows did not cover the same widespread area and some sedimentation might have gone on simultaneously with the lava flows in areas, not immediately covered by the latter. The contact between the Early to Middle Cretaceous sediments and the volcanics in Barpathar therefore looks like a minor, local break in the area. In the northern outcrops, however, the volcanics are overlain by the Mahadek Formation dated Maastrichtian (65 to 74 Ma) on the basis of a fossil horizon towards its conglomeratic top.

Langpar Formation: In the Cherra Plateau of Meghalaya this formation is restricted to Paleocene and the underlying Mahadek Formation in the Um Sohryngkew river section, referable mainly to the Cretaceous, is missing here due to a hiatus. Investigations on the micro-faunal change close to the K/T (Cretaceous-Tertiary) iridium layer suggest existence of dwarfed and bored Cretaceous planktonic foraminifera above the layer. The K/T planktonic extinctions in Meghalaya are not instantaneous. Predator gastropod larvae probably played a leading role in this extinction.

The size, shape and composition of the pyroclastics, their disposition in the lower part of Mahadek Formation and that of the dyke within the upper part of Mahadek Formation provide unequivocal evidence that when these sediments were deposited a volcanic environment was also present. The Cretaceous Mahadek sediments in Meghalaya rest unconformably on the Precambrian granite complex, but at places on the Sylhet Trap.

Andaman and Nicobar Islands

Andaman and Nicobar Islands contain Late Cretaceous sediments and

intrusives, which cover almost the entire island. Porlob, Serpentine and Baratang Groups of these islands extend from Late Cretaceous to Paleocene (Fig.8.18).

Porlob Group: The oldest sedimentary rocks recorded from Andaman-Nicobar Islands are porcellaneous limestones or marbles, cherts, jaspers and quartzites. At places the argillaceous rocks in contact with ultrabasic rocks have given rise to phyllites. These rocks are exposed in Porlob, Chengappa and Great Nicobar Islands. On weathering these rocks have given rise to bright red lateritic soil. The cherts have yielded Late Cretaceous radiolaria, which are useful in determining the age of the associated igneous rocks designated as Serpentine Group.

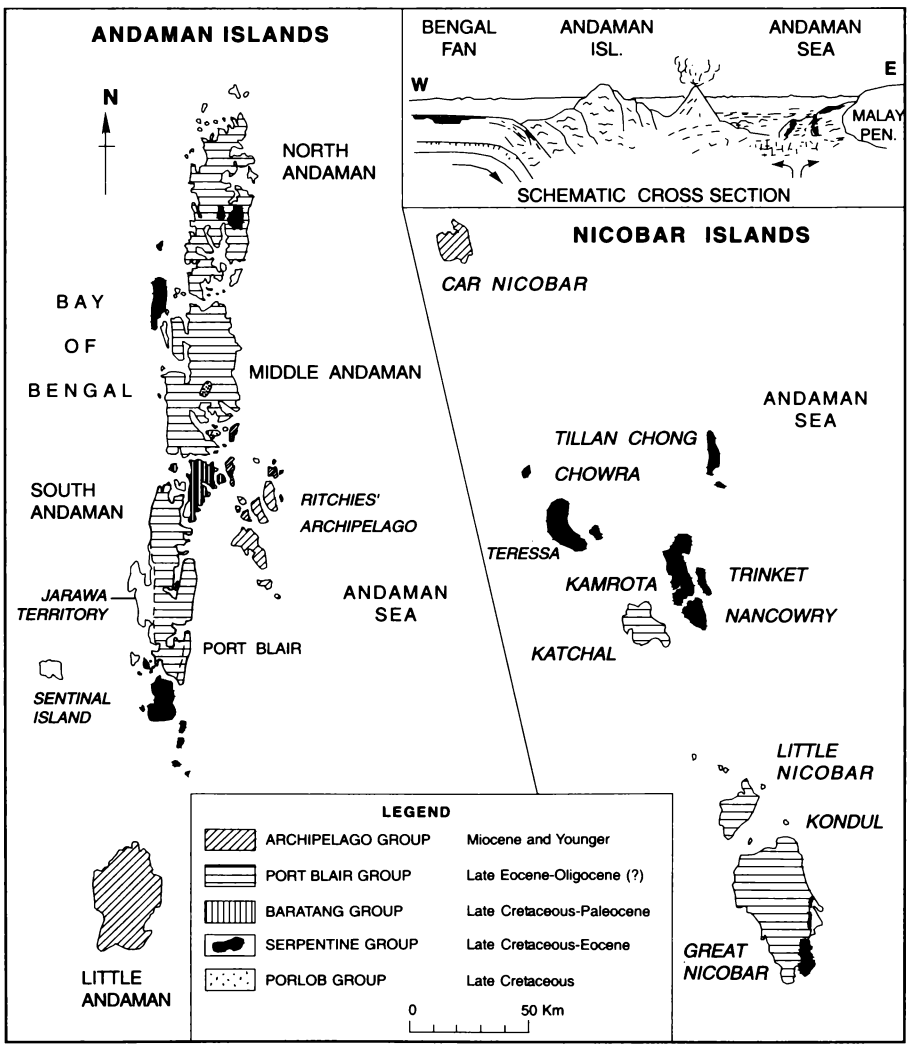


Fig.8.18. Geological map of Andaman-Nicobar islands (after Srinivasan, 1986).

Serpentine Group: This group comprises ultrabasic and basic rocks, such as gabbros, peridotites, dunites and serpentinites. Outcrops of these are met with in Saddle Peak in North Andaman, South Peak and Mount Baker in Middle Andaman. They also form the rocky islands of Rutland Island, Sister Island and Tillanchong Island. The general absence of olivine in these rocks suggests that these are probably Fe-rich tholeiitic basalts and may represent igneous activity (70-45 Ma) related probably with the Deccan Trap activity of the mainland. Good exposures of serpentinites also occur between 12 and 13 km stones along North-South road in Great Nicobar Island. These rocks have been designated as Andaman Ophiolite. They are highly sheared and altered to soft ultramafic schists and serpentine.

Baratang Group: This group, consisting of marine grey shales interbedded with limestones and siltstones, is exposed in the Baratang Island. The foraminiferal assemblage indicates an age ranging from Late Cretaceous to Paleocene.

Presence of *Rugoglobigerina rugosa, Ventilabrella glabrata,* and *Globotruncana concavata* from the ejected material of mud volcanoes in Baratang Island indicates Santonian (middle Late Cretaceous) as the lower age limit of the Cretaceous rocks. Microfaunal evidences such as Globotruncanids and Heterohelicids and *Nummulites fabianii* reported from this suggest an Upper Cretaceous –Upper Miocene age.

Cretaceous/Tertiary (K/T) Boundary

A complete K/T boundary section in low latitude sites must contain younger Cretaceous nannofossil zone, *Micula princii*, followed upwards by 'boulder clay" lying within the Tertiary planktonic foraminifer zone, *Globigerina fringa* and succeeded by *Globigerina eugbona* zone. The K/T or Mesozoic/Cenozoic boundary in India was earlier considered to be between the last ammonite and first nummulite close to the extinction level of *Nautilus danicus* Schloth. This approach includes Danian sediments of India into Cretaceous. Attempts were made earlier to demarcate K/T boundary on the basis of planktonic foraminifera in the Northeastern region of India and in Tamil Nadu. It has been possible to identify the K/T boundary precisely in the continuous marine section of Um Sohryngkew river in Meghalaya (*see* figure 9.33). Limonitic clay along this boundary of nearly 1.5 cm thickness is associated with a high concentration of iridium and other siderophile elements. Actual extinction of the Cretaceous planktonic foraminifera occurs nearly forty centimetres above the geochemically defined boundary.

9

Deccan Volcanic Province

INTRODUCTION

The Deccan Volcanic Province (DVP) covering the Deccan Plateau is one of the most remarkable continental flood basalt provinces (CFB) of the world, like those of Columbia River, North Atlantic, Caribbean, Parana, Karoo, Etendeka, Ethiopia, Siberia, Emaishan, Ontong Java and Antarctica (Fig. 9.1) The volcanics of DVP are popularly known as Deccan Traps, the term coined by W.H. Sykes in 1833 after the Swedish word "Trapp – Trappa" meaning stair-like or step-like. Deccan Trap therefore refers to the terraced appearance of the landscape of the Deccan Plateau. The word 'trap' has come to mean fine-grained, dark coloured rock, which is usually basaltic in composition. The 'traps' are called 'flood basalts' because of their vast expanse, and as 'plateau basalts' as they often stand out as tablelands.

The Deccan volcanics are exposed in the majestic hills of Western Ghats (*Sahyadri* Mountains) that form a spectacular landscape of great scenic beauty. The Western Ghats represent an anorogenic mountain range with steep escarpments to the west, parallel to the west coast of India. The *ghats* have resulted from large scale faulting to produce an Atlantic-type continental margin. Some geomorphic aspects of this region (DVP) are dealt with in Chapters 1 and 13.

Deccan Traps cover an area of 500,000 sq.km in the western and central India. Their estimated extent prior to erosion, including their concealed extensions under the Arabian Sea (Fig.9.2), may be of the order of 15,00,000 sq.km. The approximate composite thickness of the Deccan volcanics is about 3000 m. The volcanics are dominantly subaerial flows of tholeiitic basalts with subordinate picrites, picritic basalts and alkaline basalts. Alkaline basalts containing mantle nodules are exposed in the continental rifts of Narmada, Khambhat (Cambay) and Kachchh (Kutch). Volcano-plutonic complexes emplaced in Deccan basalts are spectacularly exposed in the Saurashtra horst, Khambhat graben and Narmada rift. The volcano-plutonic complexes consist

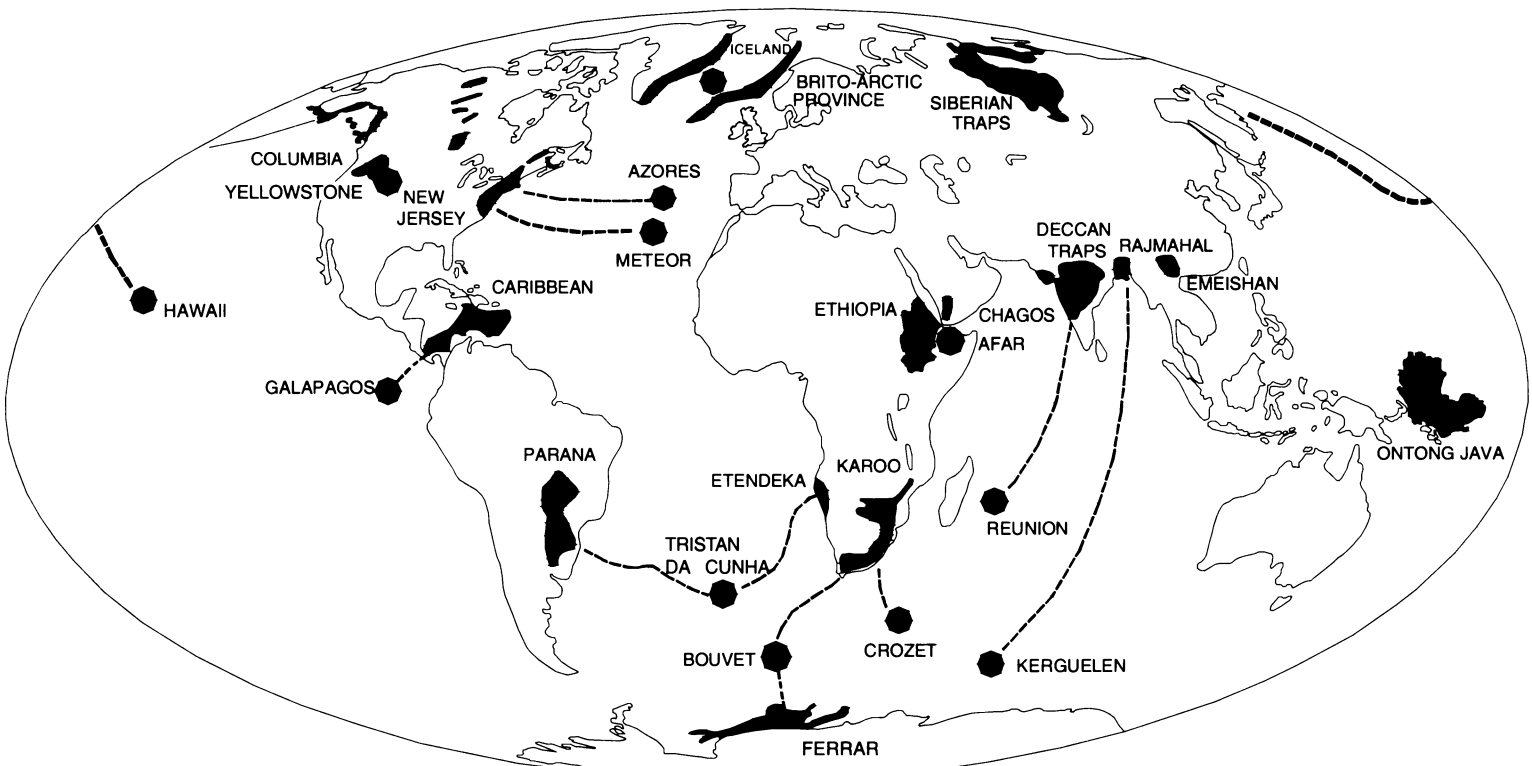


Fig.9.1. Flood basalt forming Large Igneous Provinces (LIPs) of the world along with genetic links to hotspots. For example, Deccan Traps are linked to the Reunion hotspot (modified from Courtillot, 1990).

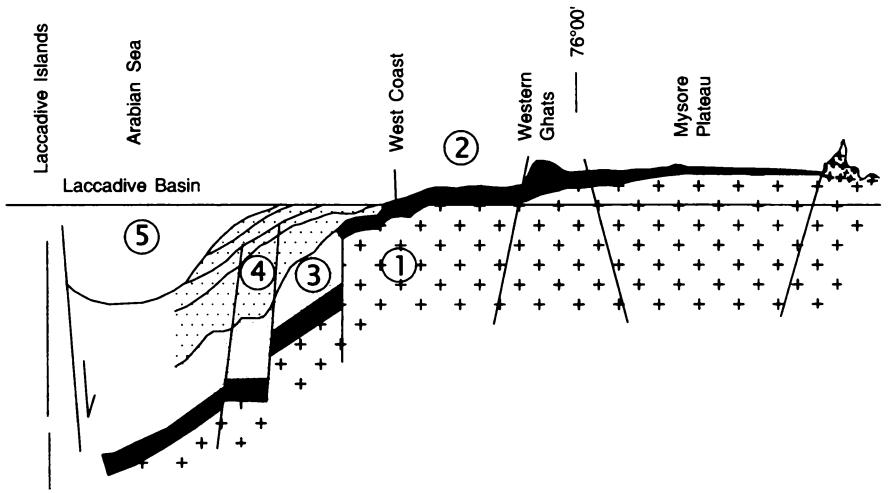


Fig.9.2. Section across the DVP from Mysore Plateau to Laccadive Basin showing the exposed and concealed extent of the Deccan Trap. **1** - Basement, **2** - Deccan Trap, **3 & 4** - Tertiary sediments, **5** - Arabian Sea (modified from Biswas, 1987).

of acid to alkaline intrusives and flows, gabbros and dolerites, as well as lamprophyres and carbonatites. This igneous ensemble of volcanics, plutons and dykes (Walker, 1993) of Deccan constitutes one of the best Large Igneous Provinces (LIP) of the world (Mahoney and Coffin, 1997).

The DVP is unique in the geology of India because of its prodigious volcanism and its pivotal role in studies of volcanology. The Deccan volcanics have erupted close to the Cretaceous-Tertiary (K/T) boundary at about 65 Ma. This stupendous volcanism is closely related to catastrophic events of mass extinction (like dinosaurs) through bolide impacts and global climatic change. DVP occupies a central place in global tectonic models of break up and assembly of the Gondwana supercontinent. The dismemberment of the supercontinent was triggered by mantle plumes and hotspots that caused the generation of LIPs (Fig.9.1)and CFBs. DVP is the largest and most conspicuous among the Phanerozoic volcanics of India (Fig.9.3).

The early pioneers who laid the foundation for the study of Deccan volcanics are T.J. Newbold, W.T. Blanford, P.N. Bose, L.L. Fermor, C.S. Fox and W.D. West. Multi-institutional international team co-ordinated by K.V. Subbarao brought about a sea change in our understanding of the Deccan Traps. A large volume of literature exists on the Deccan Traps, the most important among them being the edited volumes of Bulletin Volcanologique (v.35, Nos. 3&4, 1972), Subbarao and Sukeshwala (1981), GSI (1984, 1996), Subbarao (1988, 1994, 1999), Project CRUMANSONATA (1995) and Deshmukh and Nair (1996). Brief reviews on Deccan Traps are given by Ghodke et al. (1984), Mahoney (1988), Godbole et al. (1996), Hooper (1999), Walker (1999), Subbarao

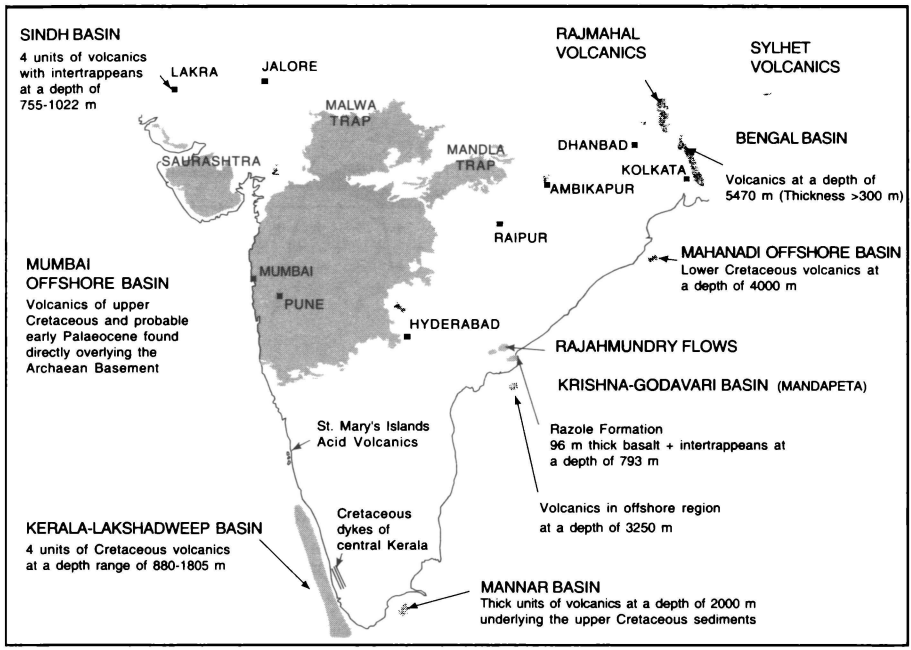

SINDH BASIN
4 units of volcanics with intertrappeans at a depth of 755-1022 m
LAKRA
JALORE
MALWA TRAP
SAURASHTRA
MANDLA TRAP
RAJMAHAL VOLCANICS
SYLHET VOLCANICS
DHANBAD
BENGAL BASIN
KOLKATA
AMBIKAPUR
Volcanics at a depth of 5470 m (Thickness >300 m)
RAIPUR
MAHANADI OFFSHORE BASIN
Lower Cretaceous volcanics at a depth of 4000 m
MUMBAI OFFSHORE BASIN
Volcanics of upper Cretaceous and probable early Palaeocene found directly overlying the Archaean Basement
MUMBAI
PUNE
HYDERABAD
RAJAHMUNDRY FLOWS
KRISHNA-GODAVARI BASIN (MANDAPETA)
St. Mary's Islands Acid Volcanics
Razole Formation
96 m thick basalt + intertrappeans at a depth of 793 m
Volcanics in offshore region at a depth of 3250 m
KERALA-LAKSHADWEEP BASIN
4 units of Cretaceous volcanics at a depth range of 880-1805 m
Cretaceous dykes of central Kerala
MANNAR BASIN
Thick units of volcanics at a depth of 2000 m underlying the upper Cretaceous sediments

Fig.9.3. Map of Peninsular India showing distribution of both surface and subsurface volcanics (Misra, 2005).

et al. (2005), Nair and Bhusari (2001) and Chandrasekharam (2003). Alkaline rocks of DVP are summarised by Gwalani (2004 and references therein). Carbonatites of DVP and elsewhere are reviewed by Krishnamurthy (1988) and Srivastava and Hall (1995).

FIELD FEATURES OF BASALTIC FLOWS

Terminology: In field mapping of the Deccan Traps, several terminologies are in common use. *Lava flow* refers to the product of a simple eruptive event. Lava flows are built of *flow units* called *lobes* (Fig.9.4a). Small lobes are called *toes.*

Lava flows are primarily of two types called (i) *pahoehoe* having a base marked by pipe amygdales and the top by an amygdaloidal zone, capped by a surface having ropy structure, and (ii) *aa* having an upper layer of rubble or flow breccia. Transformation of *pahoehoe* to *aa* flows is evidenced by slabby *pahoehoe* flows (Duraiswami et al. 2003). Lava flows are classified as *simple* or *compound* flows. Simple flows consist of a single lobe. They have joints perpendicular to the lower contact. Compound flows (Fig.9.4 b,c) may be as thick as 100 m and may be made of lobes 10 cm to 10 m thick, consisting of pahoehoe and/or aa lavas. Compound flows show a wide variation in petrography and are extremely widespread in Deccan Traps. A *lava sequence* consists of

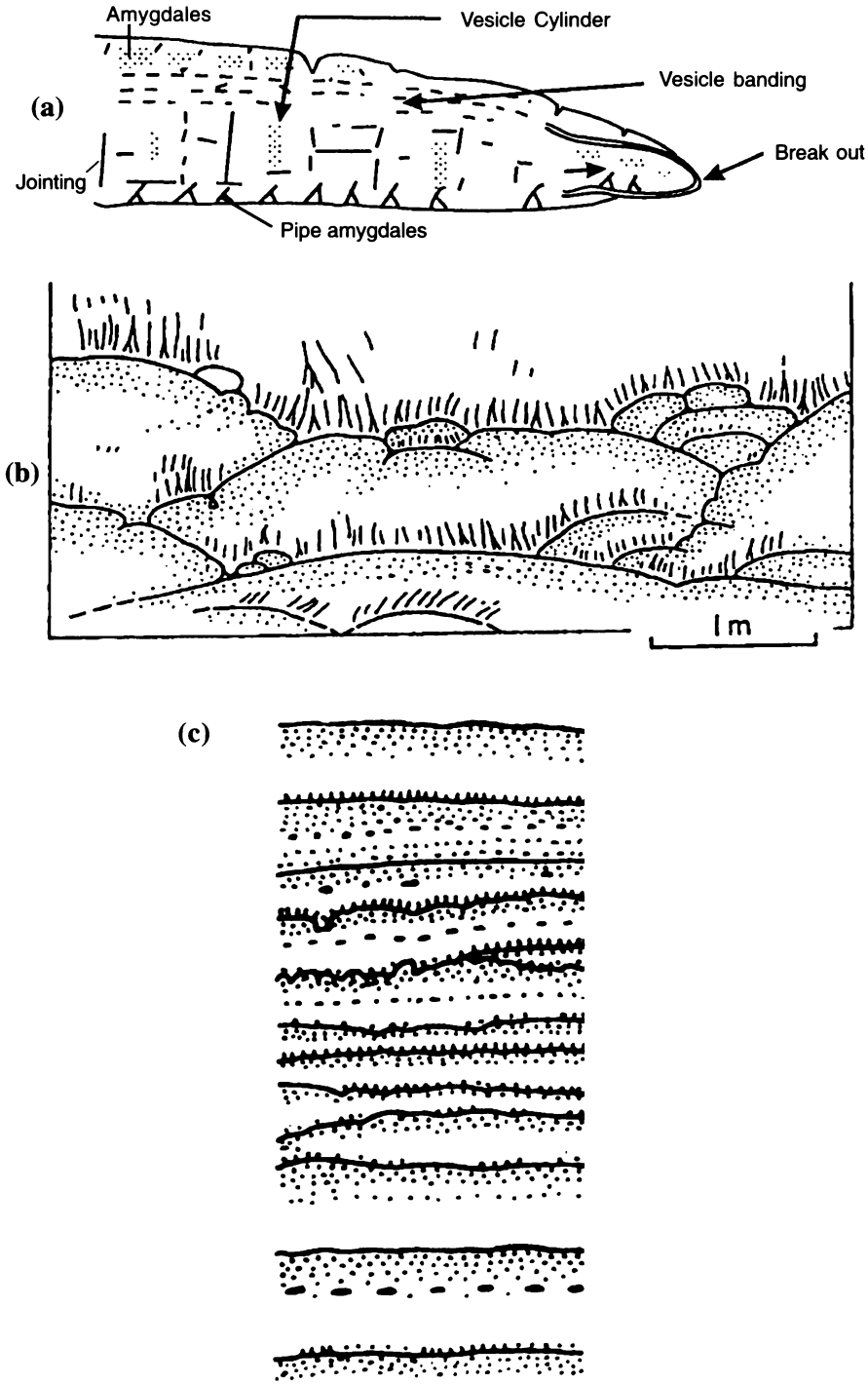


Fig.9.4. (**a**)Lobe of a simple pahoehoe flow (after Bondre et al. 2000). (**b**) Outcrop of a compound pahoehoe flow (Walker, 1999). (**c**) Schematic vertical section of a compound lava flow (Walker, 1999).

individual flows which are distinguished by textures (e.g., aphyric, microphyric, porphyritic etc.), by phenocrysts (plagioclase, pyroxene, olivine etc.) and by geomorphic expression (cuestas, hogbacks, cliffs, deep valleys etc.).

The emplacement of flow is through the process called *inflation* (Bondre et al. 2004), which causes the thickening of the lobes by continued injection of lava. The flow front advances through break-outs as lava toes. The flow becomes convex up (Fig.9.5a). Rising fluid causes vesicle banding. Stagnation causes vesicle cylinders and jointing (Fig.9.4a). The common inflation features are called *tumuli* (Fig.9.5b,c), which are whaleback-shaped mounds with axial cracks. The tumuli are usually 50 to 100 m long and 10 to 20 m tall. Their

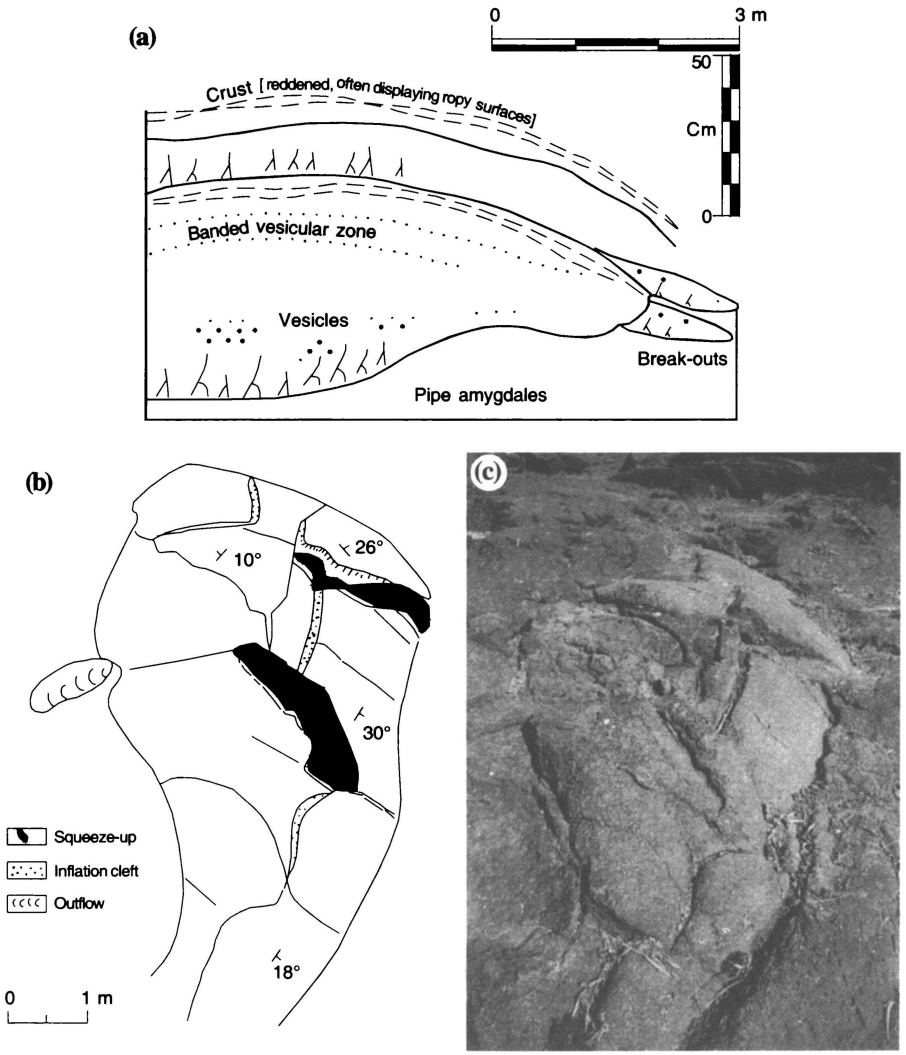


Fig.9.5. (**a**) Features of inflation of a pahoehoe lobe (Bondre et al. 2000). Sketch (**b**) and photograph (**c**) of flow lobe *tumuli* with radial cracks (Duraiswami et al. 2002).

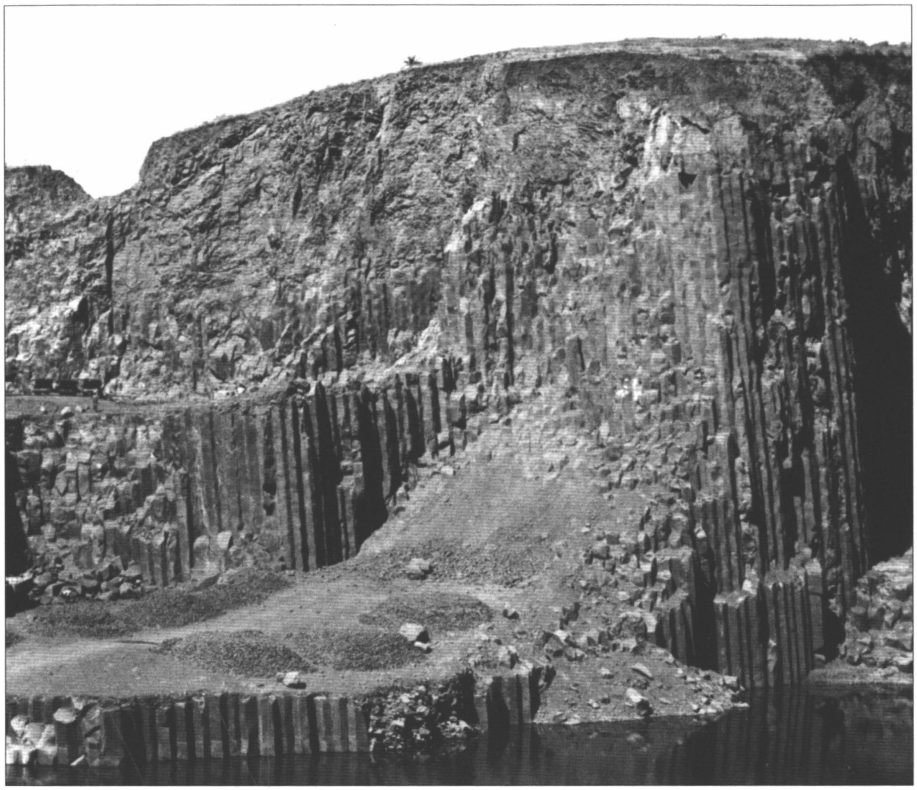


Fig.9.6. Columnar jointing of Deccan basalts near Andheri, Mumbai (courtesy: K.V. Subbarao).

presence in Deccan lavas suggests comparison with Hawaiian lavas where tumuli are widespread. The process of inflation produces a distinctive internal structure within each lobe in respect of jointing, vesiculation and texture. Pillow lavas, pyroclastics and spiracles (steam injection structures) suggestive of subaqueous origin are seen locally. The jointing types in lavas are variously described as columnar, platy, hackly etc., among which the columnar structure is the most spectacular and widespread (Fig.9.6). Sometimes genetic terms like colonnade and entablature are used to describe the types of jointing. Lava flows develop preferred pathways to deliver the lava from the vent to the flow front. These pathways occur in the form of lava channels (Fig.9.7a,b) or as lava tubes (Misra, 2002), forming an arterial system around effusive centres. Pahoehoe flows are generally localised in tubes, whereas aa flows prefer channels.

Giant Plagioclase Basalts (GPBs) or Megacrystic Horizons are valuable markers for mapping the lava stratigraphy (Fig.9.8a). GPBs are flows that contain unusually large plagioclase phenocrysts (>30 mm in size), which have an average compositional range of $An_{60\text{-}65}$. GPBs are among the most evolved flows having the largest abundances of incompatible elements (P, Ti, Zr) and

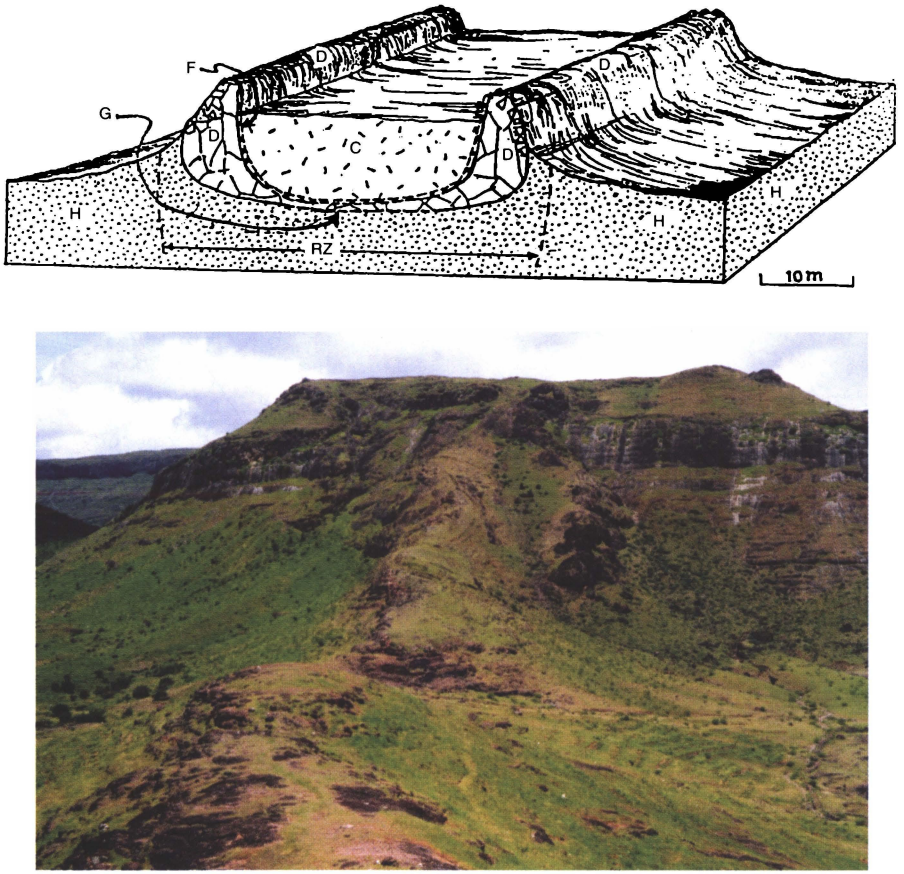


Fig.9.7. (**a**) Schematic diagram of a lava channel. **C** - core. **F** - rim of glassy basalt. **D** - levees. **G** - floor of the channel. **H** - host basalt. **RZ** - zone of reddening and induration (Thorat, 1996). (**b**) Sinuous parallel ridges of levees in a lava channel near Ahmednagar. The remnant channel consists of indurated and reddened basalt. (Courtesy: K.S. Misra).

the smallest Mg numbers. Their mineralogical and chemical compositions, particularly in respect of critical oxides viz., TiO_2, P_2O_5, K_2O and trace elements of Ba, Zr, Nb, Y and Cu, contrast sharply with those of the adjacent flows. This chemical fingerprinting has been possible despite their wide compositional range and porphyritic texture, which generally increases compositional scatter. The compositional range of the GPB flow is attributable to various degrees of crystal fractionation. There is another view that GPBs perhaps represent a dormant stage in the fractionation process. Since the GPBs normally overlie red boles suggesting a pause in volcanism, the dormancy view finds some support.

Bole beds are considered as marker horizons, which are valuable in the delineation of flows. They are commonly termed as red boles (Fig.9.8b) and green boles or green earth. Boles (fossil laterites) are composed of pyroclasts

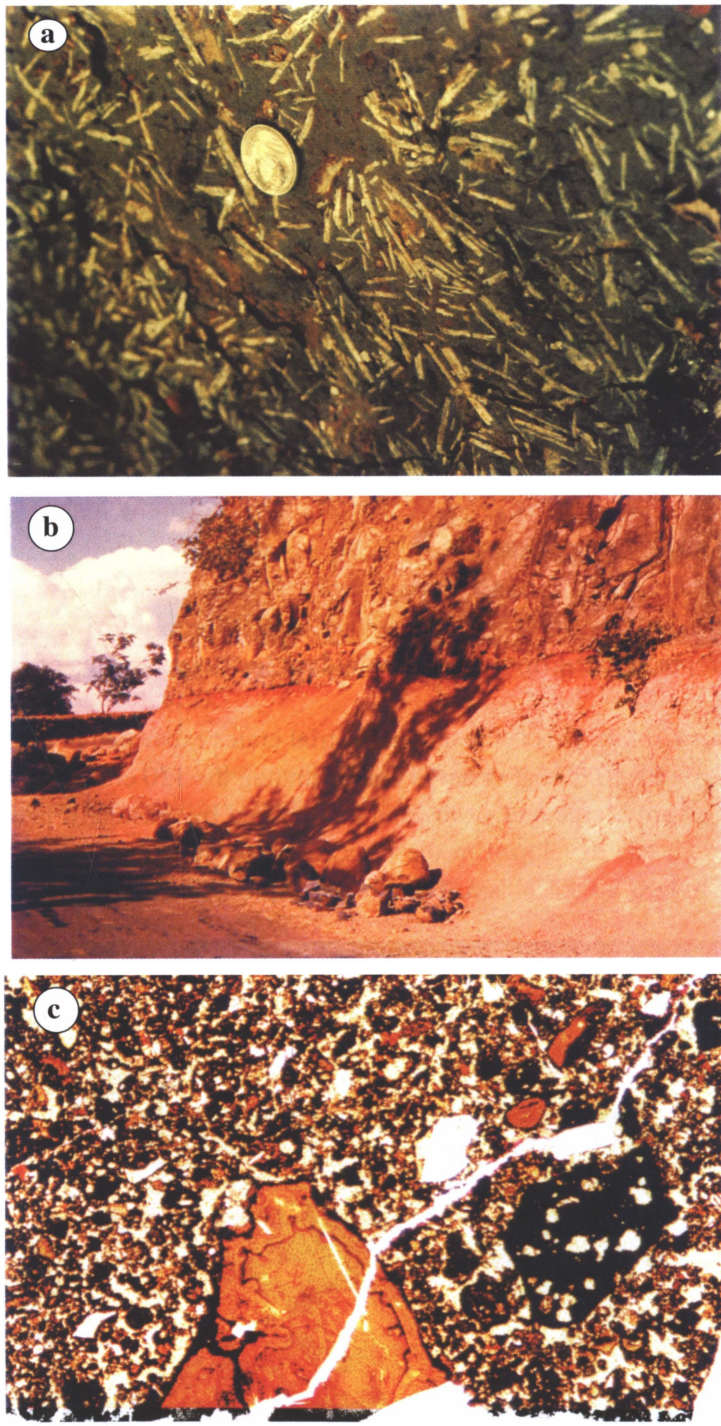


Fig.9.8. (**a**) Photomicrograph giving typical textural and mineralogical characters of Giant Plagioclase Basalt (GPB), Thalghat. (**b**) Red bole horizon at the flow contact between two flows of Poladpur Formation, Simhagad Fort, Pune. (**c**) Photomicrograph of red bole. Altered glass fragments and glass shards are seen (Subbarao et al. 2005).

of different shapes and sizes enclosed within glass (9.8c) or fine ash particles (<10 microns). The pyroclasts have a thin marginal crust and are often sintered. The glass may be devitrified. Red boles usually contain nantronite, halloysite, iron oxide and silica. Green boles usually consist of illite, quartz and plagioclase. Bole beds are regarded as tuffs, the red bole being of basic composition whereas the green bole is of acid to intermediate composition. After eruption of volcanic flows, pyroclasts are settled as ashes consolidated into bole beds.

Zeolites occur as infillings in vugs, pipe amygdules and veins, and they help in the demarcation of flows. The distribution of zeolites into three zones laumontite, scolecite and heulandite cutting across the basalt stratigraphy was proposed earlier, but later studies showed its random distribution. The common zeolites found in the Deccan basalts are heulandite, stilbite, mordenite and apophyllite (Fig.9.9). Laumontite and scolecite are of restricted occurrence. Fine zeolite crystals in vugs are collector's items in the world gem market. These are elegantly displayed in Gargoti Museum at Nashik. The Deccan zeolites are remarkable for their compositional purity. They are generally rich in Si, Al, Na, Ca, Ba and Sr with Ca predominating over Na. The zeolites are believed to have been precipitated from meteoric fluids at low temperatures of ~ 100°C.

Lonar Crater: This is the only terrestrial crater excavated in basalt in the world (Fig.9.10a,b). Lonar crater is unique among the 120 craters on the earth in that it is fairly large and young and unmodified by erosion. It is a circular structure that has developed in the Deccan basalt during Quaternary, and is unrelated to Deccan volcanism. The circular depression cradles a saline lake in

Fig.9.9. Zeolite in Deccan basalt (courtesy: K.V. Subbarao)

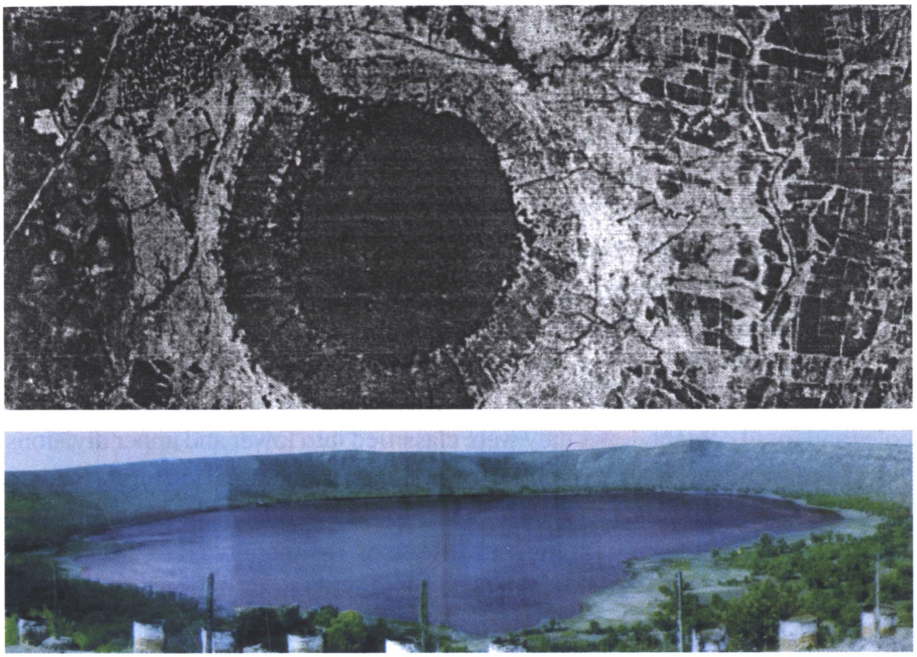


Fig.9.10. (**a**) Aerial view of Lonar Lake (Fredriksson et al. 1973). (**b**) Panoramic view of Lonar Lake (GSI, 2001, p.51).

the central portion. The crater is situated in the Buldana District of Maharashtra and is one of the National Geological Monuments (GSI Spec. Publ. No.61, 2001, p.51).

There was speculation on whether the crater was due to explosive volcanism, land subsidence or meteoric impact. The presence of lava channels/ tubes, volcanic debris and red tuff in the vicinity of the crater and similarity of REE of basalts in the crater and the surroundings support the explosive volcanic origin. Investigations by the Geological Survey of India revealed shock ejecta scattered as far as 600 m away from the crater. Shock breccia containing veins, pseudo-flow structures and scatter cones and brecciated basalt up to 335 m depth has been found by drilling. Plagioclase has been converted to maskelynite by impact. Rock melts containing veinlets, spherules and bombs are also found. All these features suggest the impact origin of Lonar crater. The crater has been compared to the 'fluidised' craters of Mars.

REGIONAL STRATIGRAPHY

The Deccan volcanics have erupted through the Precambrian crust of Dharwar, Bastar, Aravalli and Bundelkhand cratons as well as the Satpura mobile belt. At places they are underlain by Cretaceous sediments (e.g., Bagh, Lameta, Dharangadhara and Wadhawan sequences), which are commonly

described as Infra-trappean sediments or merely as Infra-trappeans. The lava pile has also many intercalated sediments and ash beds (red bole, green earths etc.), which are commonly known as Inter-trappeans.

Deccan basalts are nearly horizontal over vast areas, except where they are tectonically disturbed as in the West Coast, Western Ghats, Khambhat graben and Son-Narmada (SONATA) rift. The lavas are thinnest in the east and they progressively thicken to about 2 km in the west. This variation is attributed to pre-Deccan topography as well as renewed faulting and scarp development.

Historically, the Deccan volcanics were classified into three stratigraphic units, viz., the Lower, Middle and Upper, on the basis of inter-trappean beds, boles and fossil content. Later they were classified into lower and upper divisions based independently on magnetic reversals and chemical criteria. Recent geological surveys by the Geological Survey of India and geochemical mapping by a multi-national team with Indian Institute of Technology (IIT), Mumbai as the nodal agency have significantly enhanced our knowledge of the Deccan Traps and brought out new stratigraphic schemes. These studies have also shown that the stratigraphy youngs from west to east, rather than in the reverse direction (east to west) as postulated earlier.

The lithostratigraphy of Deccan volcanics consists of formations and subgroups. A sequence of flows with similar field, petrographic (Fig.9.11a, b) and gross chemical and isotopic features has been termed a formation. Formation boundaries are defined by recognizable breaks, presence of marker horizons and large chemical shifts over a wide area. The formations are clubbed together into subgroups based on types of flows (single, compound or a suitable combination of both), geochemical variations and marker horizons. The different subgroups are combined into a group called as Deccan Basalt Group or Sahyadri Group.

Lithostratigraphy has been worked out in detail for the region of Western Maharashtra from Tapti river in the north to Belagaum in the south, and from Aurangabad in the east to the West Coast covering an area of 1,50,000 sq. km, which is over one-third of the exposed area of DVP. Stratigraphic correlation over such a vast area has limitations such as monotonous similarity of lava flows, lack of marker horizons on such a large scale, and complexity caused by erosion and structural disturbances. However, regional gradient of the flows in undisturbed areas and marker horizons such as Giant Plagioclase Basalts (GPBs) are successfully used to erect a regional stratigraphic column, which was extended on a reconnaissance scale to the rest of the DVP.

Recently, systematic geochemical mapping using similarities and differences in elemental abundances and ratios (Fig.9.12) as well as isotopic signatures have been used to work out a chemo-stratigraphic column for the Western

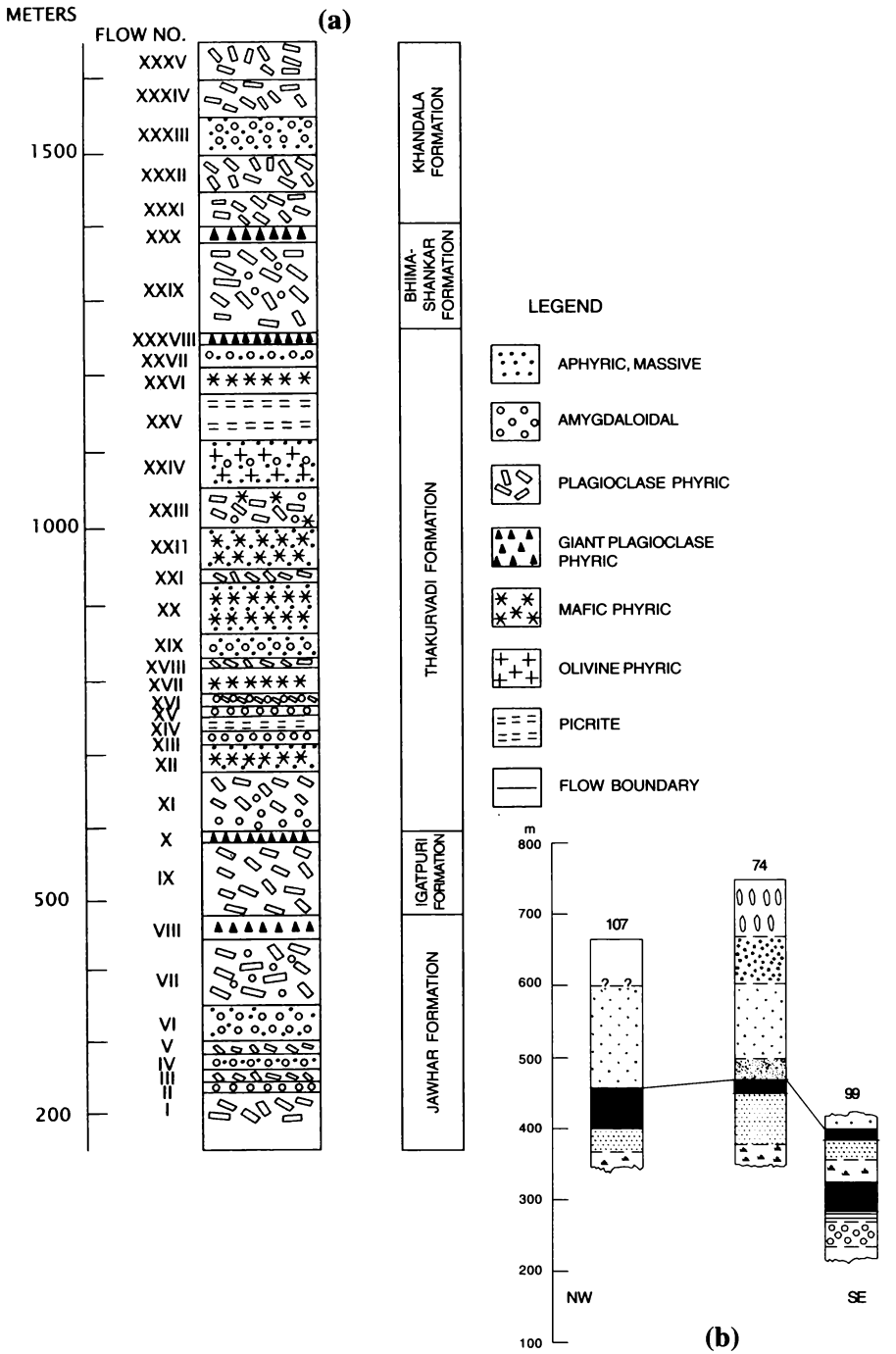


Fig.9.11. (**a**) Stratigraphic column showing delineation of formations using field and petrographic criteria. Note GPBs marking the formation boundaries (after Khadri et al. 1988, p.164). (**b**) Stratigraphic correlation log. The black box represents GPB at the formation boundary. Other symbols refer to various basaltic types (after Bodas et al. 1988, p.251). Section: 107 - Val River; 74 - Triambak Ghat; 99 - Mokhada.

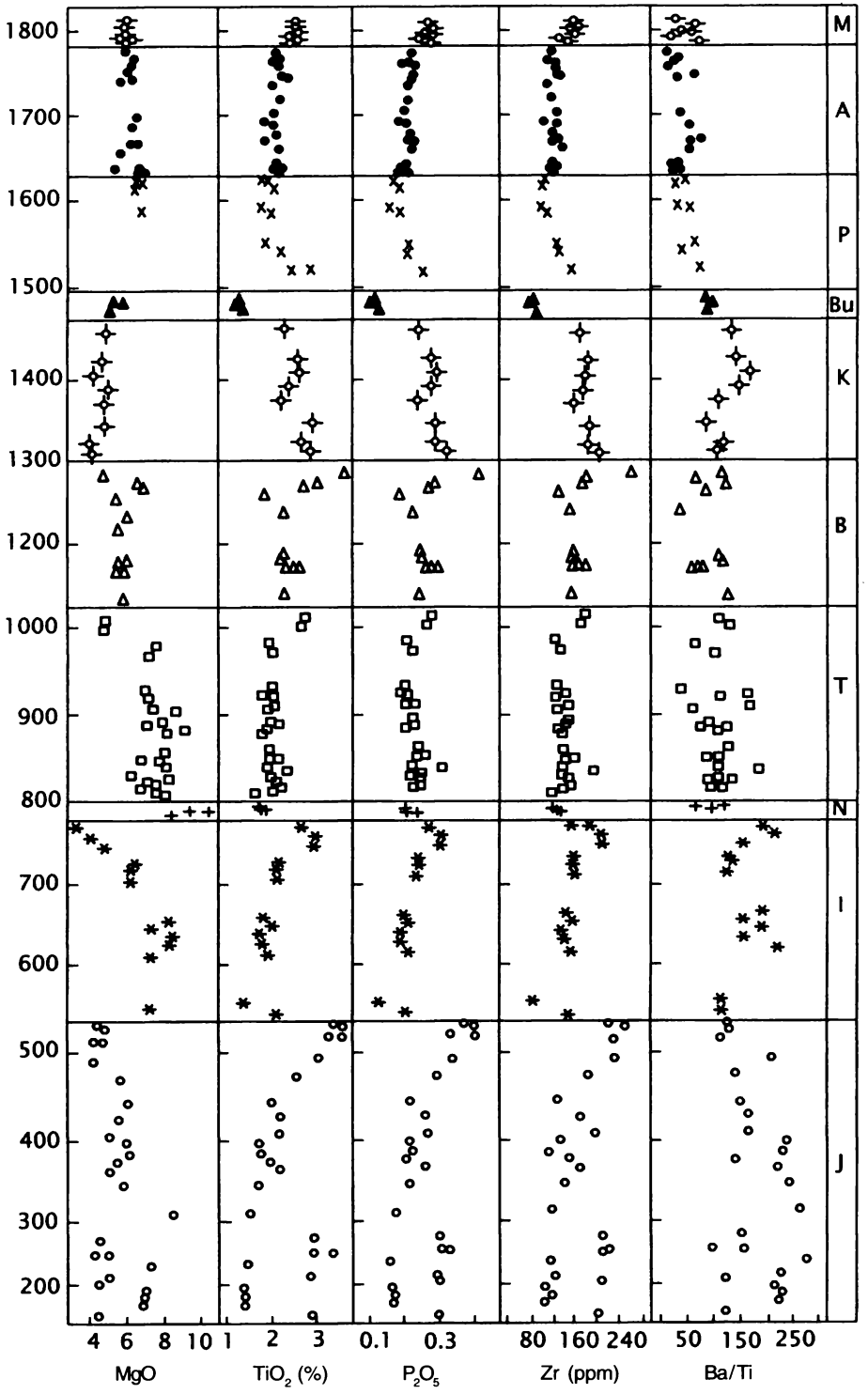


Fig.9.12. Chemical stratigraphy based on elemental abundances and ratios (Subbarao et al. 1994).

Deccan Province (Cox and Hawkesworth, 1985), especially in the well exposed geological sections in the Western Ghats from Nashik to Mahabaleshwar and from Pune to the West Coast, for the length of the Western Ghats of 500 km and approximate area of 30,000 km^2. The chemo-stratigraphy was extended to the area in the south and the east by reconnaissance chemical mapping. In regional correlation, chemical types, defined as one or more members having same chemical compositions, are used. Although this is not a reliable criterion, for want of a better alternative, the chemical type serves as a reconnaissance tool.

The stratigraphy based on different attributes, such as lithological and chemical, may not show one to one correspondence, although a general unity of stratigraphy is the ultimate aim of a stratigrapher. However, a broad correspondence between chemical and lithostratigraphy has been achieved in Deccan Traps and compared with magneto-stratigraphy to obtain a holistic picture. The type area for lithostratigraphy is western Maharashtra and for chemostratigraphy is the Western Deccan Province including the well-exposed Western Ghats. Both the type areas form part of subprovinces of Main Deccan Plateau. The different subprovinces of DVP (Fig.9.13) are described below:

SUBPROVINCES

The Deccan Volcanic Province is broadly divided into four sub-provinces.

(1) *Main Deccan Plateau:* The plateau occurring to the south of Narmada River includes the Western, Central and South-Eastern areas of DVP. The Western area consists of the Western Ghats and the West Coast from Mumbai to Ratnagiri, which is the best-studied area of the Deccan Traps. The Central area covers the terrain around Aurangabad. The South-Eastern area covers the terrain around Gulbarga and Nanded.

(2) *Malwa Plateau:* The plateau is situated to the north of Narmada river covering the terrain around Sagar, Bhopal and Indore (Mhow or Mau). The Satpura Hills between the Narmada and Tapti faults form lofty peaks in the Son-Narmada rift situated between the Main Deccan Plateau and Malwa Plateau.

(3) *Mandla Lobe:* This terrain covers the easternmost outlier around Jabalpur, Seoni and Chhindwara.

(4) *Saurashtra Plateau:* This terrain covers the square-shaped plateau bounded by the Khambhat graben in the east and the western extension of Son-Narmada fault in the south. The small curvilinear outcrops of Kachchh rift are also included in this sub-province.

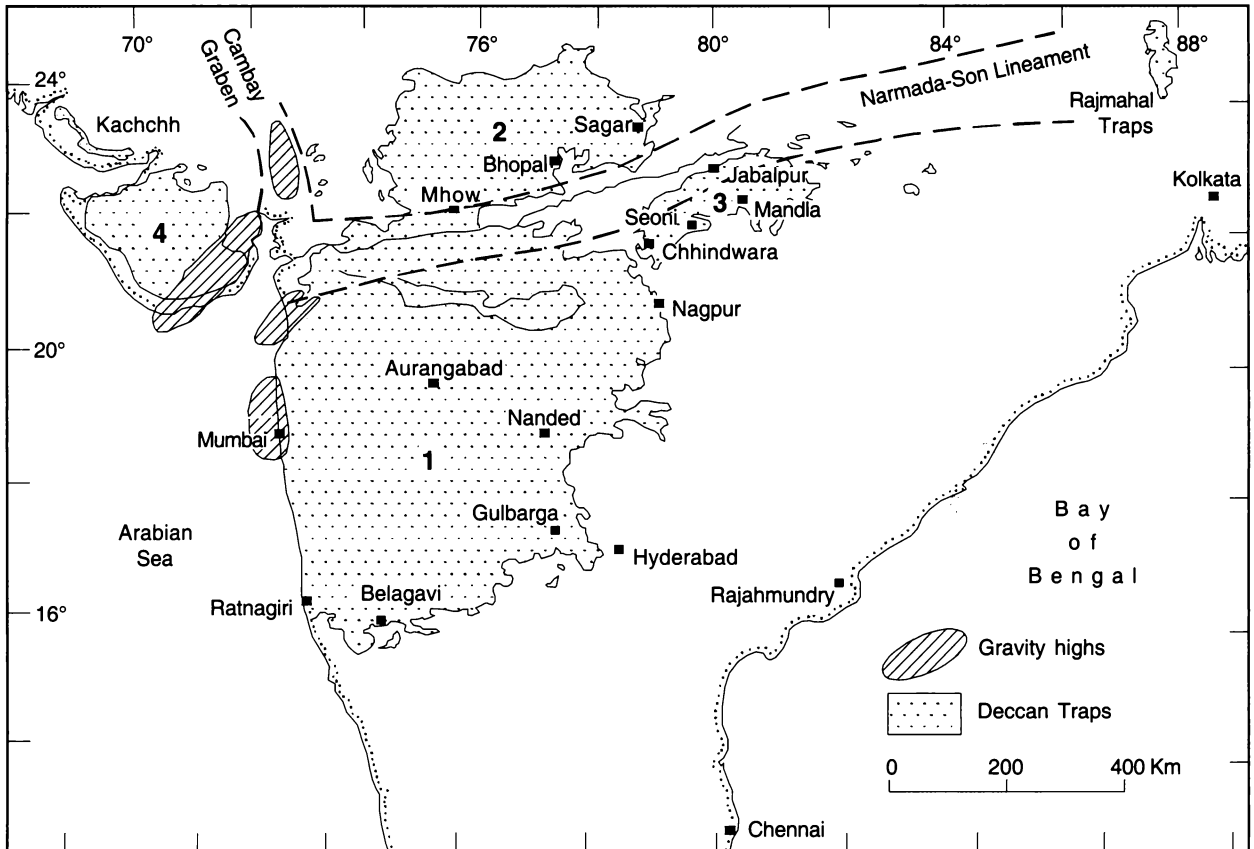


Fig.9.13. Distribution of subprovinces of the DVP. **1** - Main Deccan Plateau; **2** - Malwa Plateau; **3** - Mandla Lobe; **4** - Saurashtra Plateau and Kachchh.

An outlier of Deccan Trap is seen near Rajahmundry on the East Coast. Several sub-surface outcrops of basalts are seen in the Phanerozoic coastal sediments, some of which belong to Deccan Trap and others of different ages (Fig.9.3).

Main Deccan Plateau

The best-studied area of Deccan basalts is the Western Deccan Province (WDP) covering mainly the Western Ghats. The type stratigraphy of the WDP is extended to the Central, Southern and South-Eastern sections of the Main Deccan Plateau on reconnaissance scale.

Lithostratigraphy

The lithostratigraphic scheme proposed for western Maharashtra (Fig.9.14) by Godbole et al.(1996), suitably altered to conform to stratigraphic codes is given below in Table 9.1.

Table 9.1. Lithostratigraphy of western Maharashtra

Group	Subgroup	Formation	Thickness (m)
	—	Mahabaleshwar	600
	Wai	Purandhargad	
Sahyadri		Diveghat	900
	Lonavala	Karla	
		Indrayani	700
		Ratangad	
	Kalsubai	Salher	~1500

Salher Formation consists of simple pahoehoe flows of phyric to feldspar phyric type in the northwest. The overlying Ratangad Formation comprises compound flows of phyric and feldspar phyric type separated from the lower Salher Formation by GPB, known also as Megacryst Horizon. This formation, divided informally into lower and upper units, is exposed in the north and northwest. Separated from the Ratangad Formation by a GPB horizon is the overlying Indrayani Formation consisting of simple flows of columnar jointed and aphyric types exposed in the central part. The next unit of Karla Formation consists essentially of compound pahoehoe flows exposed in the central part. The lower part of this formation, exposed in the Elephanta and Alibagh areas, is sometimes described as Elephanta Formation. The overlying Diveghat Formation consists of aphyric aa flows with a rare pahoehoe marker. The next unit is the

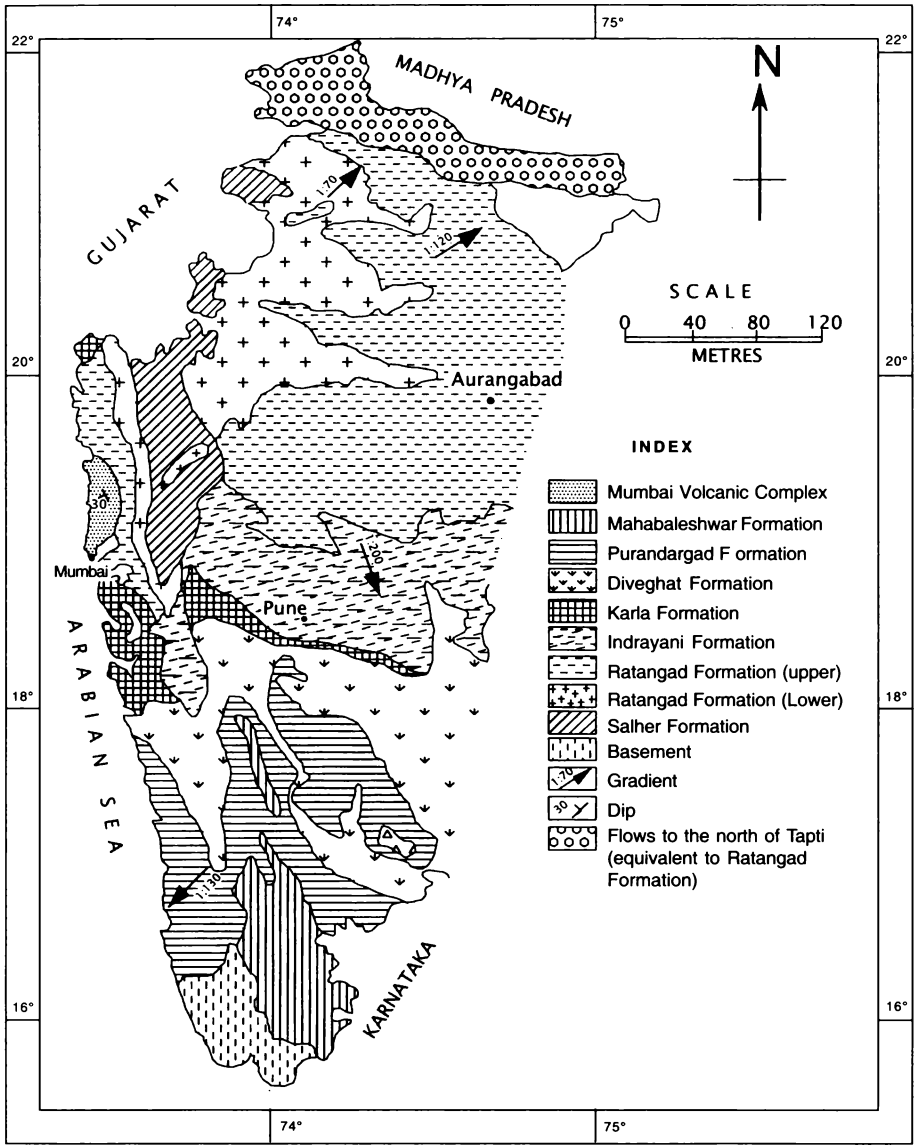


Fig.9.14. Lithostratigraphic Map of Western Maharashtra (after Godbole et al. 1996).

Purandhargad Formation consisting mainly of aa and simple flows, with compound flows in the upper part. The overlying Mahabaleshwar Formation is separated from the lower unit by a GPB horizon and comprises aa and simple felspar-phyric flows, exposed in the southern part.

The area around Mumbai consists of a different assemblage of volcanic rocks consisting of basaltic, andesitic, trachytic to rhyolitic flows associated with felsic to mafic volcaniclastics. Gabbroic to granitic intrusions are locally found. This assemblage is considered to be younger (~53 Ma?) than the

main Deccan Traps, and is called by some authors as Mumbai Volcanic Complex or Borivali Formation.

In summary, it may be mentioned that the older formations consisting of compound pahoehoe flows are exposed in the north and northwest. The younger formations are made of simple aa flows exposed in the east and south, indicating a general younging to the southeast.

Chemical Stratigraphy

The inter-university team (Subbarao et al. 2005) divided the Deccan Basalt Group into twelve formations, which are combined into three subgroups (Table 9.2; Figs.9.15a,b, 9.16a, b & c). Areas dominated by simple and compound flows and distribution of dyke swarms are shown in inset to Fig.9.15b, after Bondre et al. (2006).

Kalsubai Subgroup consists of five formations (Table 9.2) represented by amygdaloidal compound flows. Picrites (>18% MgO) and picritic basalts (>10% MgO) containing olivine and/or clinopyroxene phenocrysts are relatively common. GPBs with plagioclase, 2 to 5 cm long, separate each of the five formations of Kalsubai Subgroup.

Table 9.2. Chemical Stratigraphy of Western Deccan Province

Group	Subgroup	Formation	Magnetic Polarity
DECCAN BASALT	Wai (~500 m)	Desur	N
		Panhala	N
		Mahabaleshwar	N
		Ambenali	R
		Poladpur	
	Lonavala (525 m)	Bushe	R
		Khandala	R
	Kalsubai (2000 m)	GPB	R
		Bhimashankar	
		GPB	R
		Thakurvadi	
		GPB	R
		Neral	
		GPB	R
		Igatpuri	
		GPB	R
		Jawhar*	

GPB - Giant Plagioclase Basalt. N - Normal. R - Reverse. *Also written as Jawahar

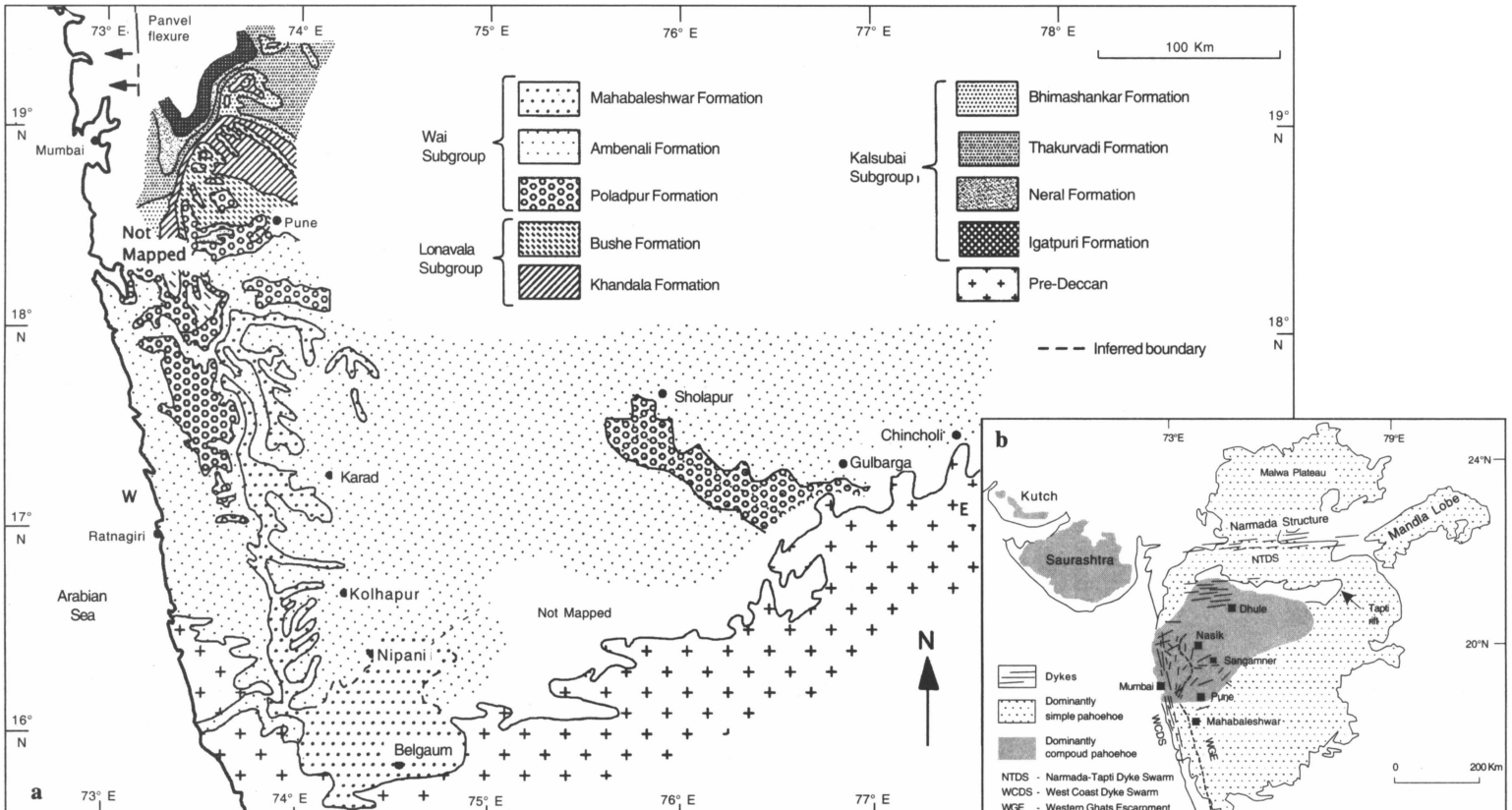


Fig.9.15. (**a**) Chemostratigraphy of the Western Deccan Province (after Subbarao and Hooper, 1988). (**b**) Areas dominated by simple and compound pahoehoe flows and dyke swarms after Deshmukh (1988), Walker (1999) and Bondre et al. (2006).

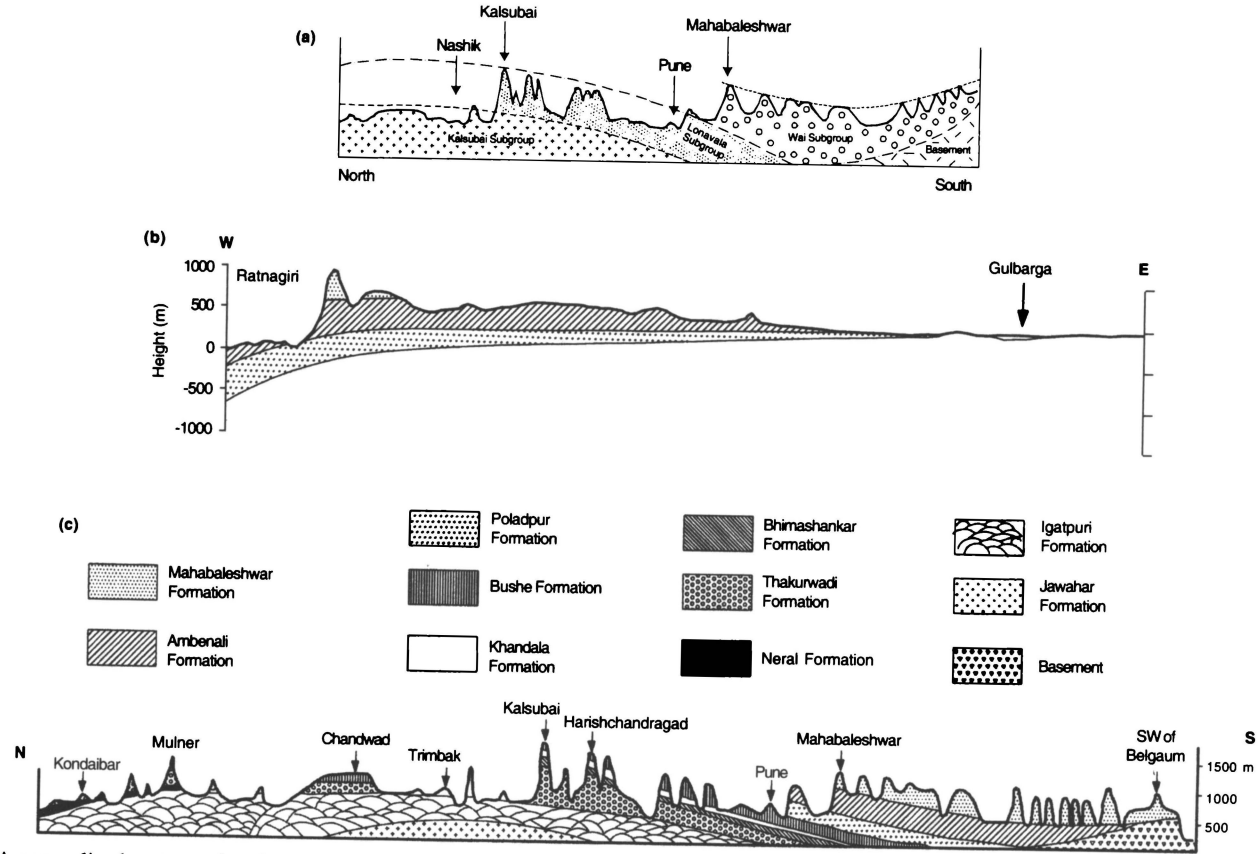


Fig.9.16. (**a**) A generalised cartoon showing the three subgroups of Deccan Basalt Group (Subbarao et al. 2005). (**b**) E-W cross-setion of DVP from Ratnagiri to Gulbarga (modified from Mitchell and Cox, 1988). (**c**) N-S cross section of DVP from Narmada River to Belgaum (Belagavi) (after Hooper, 1999).

Lonavala Subgroup consists of the lower Khandala Formation which marks a distinctive change from the Kalsubai Subgroup by the presence of simple flows having clear-cut differences in petrology and geochemistry. The upper Bushe Formation consists of coarse grained, aphyric, amygdaloidal compound flows having a narrow chemical range. Lonavala Subgroup is characterised by high Ba/Ti and Ba/Sr values and higher MgO for given TiO_2 values.

Wai Subgroup forms the upper part of stratigraphic succession with five formations (Table 9.2) consisting mainly of simple flows having well developed flow tops. The junction between Lonavala and Wai Subgroups is clearly identified in the field, which is also reflected in sharp elemental and isotopic change. The flow compositions of Wai Subgroup are more evolved than that of the older flows, but some rare picritic flows are locally encountered.

Comparison of Lithostratigraphy and Chemostratigraphy

There is a broad general correspondence between the lithostratigraphy and chemostratigraphy for the Western Deccan Province (Table 9.3), which is reflected in the GPB horizons marking stratigraphic breaks. The critical difference is in the Wai Subgroup, where two younger formations (Panhala and Desur) overlying Mahabaleshwar Formation are identified by chemostratigraphy, but such a distinction is not sustainable on lithostratigraphic grounds where only one major unit of Mahabaleshwar Formation is recognised. This difference is to be resolved by further detailed studies.

Magnetostratigraphy: The entire lava pile including the Kalsubai and Lonavala Subgroups, as well as the lower two formations (Ambenali and Poladpur of Wai Subgroup), is reversely magnetised with the exception of local normal magnetisation in thin flows. This means that nearly 95% of ~3000 m thick Deccan lavas are reversely magnetised. The top portion of the stratigraphy of the Western Deccan Province (Mahabaleshwar Formation and younger formations of Wai Subgroup) shows normal magnetisation. This top-normal characteristic may be used as a significant marker in mapping the DVP.

In the *central part* of the Main Deccan Plateau around Aurangabad and Ahmadnagar, the stratigraphy of the WDP continues uninterruptedly with the prominent GPB marker overlying Kalsubai Subgroup (Ratangad Formation). In the Ajanta Hills, compound flows corresponding to the top of Kalsubai Subgroup are well exposed. Sinuous lava channels in the area indicate the typical mode of propagation of compound flows (Fig.9.7b). Younger formations of Lonavala and Wai Subgroups appear to the east of Ajanta Hills, and older lithological

Table 9.3. Comparative table of lithostratigraphy and chemostratigraphy

Lithostratigraphy		Chemostratigraphy		Magneto-stratigraphy
Subgroup	Formation	Subgroup	Formation	
			Desur	N
	Mahabaleshwar		Panhala	N
	--- GPB ----		Mahabaleshwar	N
Wai		Wai		
	Purandargad		Ambenali	R
--------	Diveghat		Poladpur	R
————	————	————	————	R
Lonavala	Karla	Lonavala	Bushe	R
	Indrayani		Khandala	
————	--- GPB ----	————	--- 2GPBs ---	R
	Ratangad with intercalated GPB			R
			Bhimashankar	
	--- (GPBs) ---		--- GPB ----	
			Thakurvadi	R
Kalsubai		Kalsubai	--- GPB ----	
			Neral	
			--- GPB ----	R
			Igatpuri	
	Salher		--- GPB ----	
			Jawhar	

units are progressively overstepped. The lower stratigraphic units here are rarely magnetised, with a scatter on the top.

In the *southern and southeastern part* of the Main Deccan Plateau towards Belgaum and Hyderabad respectively, the Deccan lavas form a monotonous succession. Ambenali Formation extends up to Gulbarga with two inliers of Poladpur Formation exposed to the south of Sholapur near Chincholi. In the south towards Belgaum, Mahabaleshwar Formation shows extensive development with isolated patches of the younger Panhala Formation exposed to the southwest of Kolhapur. Where the Deccan volcanics overlie the Archaean granitic basement in the south, small patches of Desur Formation capping the larger patches of Panhala Formation are seen near the unconformable contact with the basement. The area south of Pune shows reverse to normal magnetic polarity corresponding to the transition from Ambenali to Mahabaleshwar Formations.

The regional stratigraphic relations in the Main Deccan Plateau clearly show that the younger formations progressively overstep the older stratigraphic units towards the south. Although such a relation is not very clear towards the southeast, it is surmised that an E-W line passing through Kolhapur may mark the overstepping of Poladpur and Ambaneli Formations by the Mahabaleshwar Formation, indicating a possible north to south stratigraphic polarity.

Satpura Hills

The Deccan volcanics exposed between the Narmada and Tapti river valleys constitute part of the Satpura Hills, and are also well exposed from Toranmal in the west to Chikaldara in the east. The absence of marker horizon, presence of thick alluvium, and effects of later faulting have caused problems in the correlation of the basalts in the Satpura region with that of the Main Deccan Plateau. The Deccan basalts of the Satpura region have been classified into six formations having a variable cumulative thickness of 600-800 m. Most of the lavas form compound pahoehoe flows, with GPB horizons occurring in between. These lavas are chemically comparable to the Poladpur, Ambenali, Mahabaleshwar, Panhala and Desur Formations of the Main Deccan Plateau. The Satpura lavas show Normal-Reverse-Normal (N-R-N) magnetic polarity. The lower bottom-normal polarity may be comparable with the normal magnetisation of Khandala Formation.

Malwa Plateau

In Malwa Plateau situated to the north of the Narmada river, the basalts are fine-grained to moderately porphyritic aa type flows associated with rare inter-trappean beds and are divided into five formations. These formations are chemically comparable to parts of Kalsubai and Lonavala Subgroups of the Main Deccan Plateau (Khadri, 2004). Detached outcrops of Deccan Traps are seen in the northeast near Jalore and Sirohi in Rajasthan.

Mandla Lobe

In Mandla Lobe, the Deccan basalts overlie the infra-trappean Lameta beds near Jabalpur, and rest over Precambrian gneisses of Seoni, Chhindwara, Mandla and Amarkantak areas. There are about 17 basaltic flows in the area, with simple aphyric flows in the upper part and compound pahoehoe flows in the lower part. The ~900 m thick succession of the area is divided into four formations separated by inter-trappean sediments of sandstone, clay, limestone

and black chert with plant fossils. These formations are chemically comparable to parts of Lonavala/Wai Subgroups of the Main Deccan Plateau (Shrivastava and Pattanayak, 2002).

Saurashtra Plateau

(a) *Saurashtra:* Tholeiitic basalts of Saurashtra are bound by the Khambat graben to the east and extensions of Narmada lineament in the south. These basalts have been classified into several compound and simple flows but no regional classification has been attempted so far. The most important aspect of the geology here is the presence of alkaline basalts, felsic lava complexes, intrusive igneous complexes, carbonatites and alkaline rocks as well as basic dyke swarms along or close to the Narmada lineament as well as close to the Khambat graben.

(b) *Kachchh:* Deccan Trap extends from Lakhpat to Anjar in the southern part of Kachchh and extends to the adjacent Sindh basin. Lava flows are predominantly tholeiites that overlie Jurassic sandstone. Six flows of columnar and amygdular basalts are delineated but no detailed stratigraphy and correlation with the Deccan Plateau of Saurashtra has yet been worked out. Alkaline basalts and derivatives occur as plugs, laccoliths, ring dykes, cone sheets, sills and dykes.

Rajahmundry Outlier

Volcanic rocks with intercalated sediments are exposed along the East Coast near Rajahmundry and are encountered in the drill cores of oil prospecting in the vicinity. Paleontological and geochronological evidence point to their contemporaneity with the Deccan Trap. The presence of LREE-enriched basalts and their R-N magnetic polarity suggests the correlation of Rajahmundry lavas with Ambenali and Mahabaleshwar Formations of the Western Deccan Province.

VOLCANO-PLUTONIC COMPLEXES

Narmada and Khambat rifts as well as Saurashtra arch host a series of prominent volcano-plutonic complexes in association with Deccan basalts. The Kachchh rift, on the other hand, is composed of a variety of alkaline lavas and dykes containing xenoliths and xenocrysts of mantle nodules.

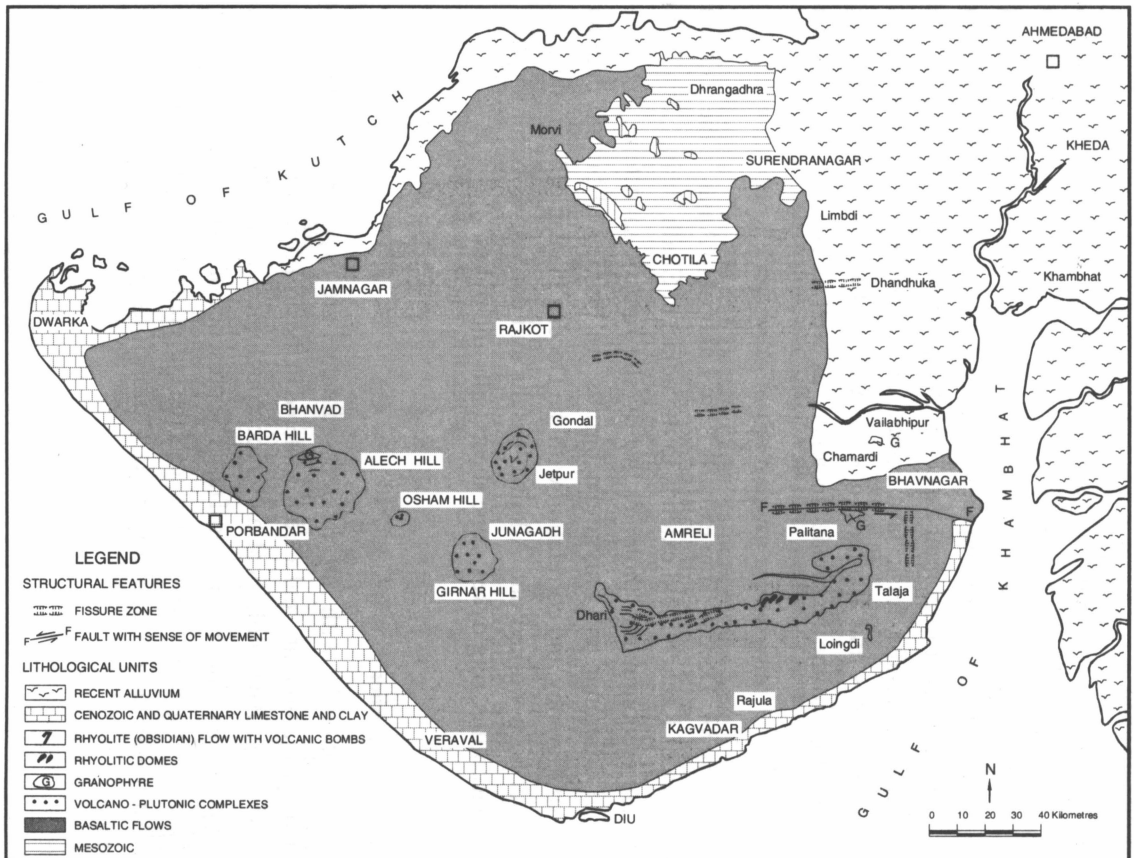


Fig.9.17. Deccan basalts and volcano-plutonic complexes of Saurashtra arch. Note the dyke swarms trending nearly E-W (after Misra, 1999).

A. Saurashtra Arch (Fig.9.17)

1. Barda hills: An arcuate body of granophyre associated with rhyolite plugs and flows occurs in the Barda hills and in the vicinity of Porbandar.
2. Alech hills: A series of concentric and inward dipping rhyolite flows is found in Alech hills, which is also close to Porbandar.
3. Osham hills : A circular hill rising abruptly from the plains near Junagadh is composed of trachytes, rhyolites and pitchstones (including perlites).
4. Girnar Complex : The largest ring complex covering about 150 km^2 occurs on the imposing Girnar hills near Junagadh (Fig.9.18). A central plug of diorite and monzonite with a ring of granophyre occurs within the periphery marked by olivine gabbro. The gabbro is intruded by dykelets

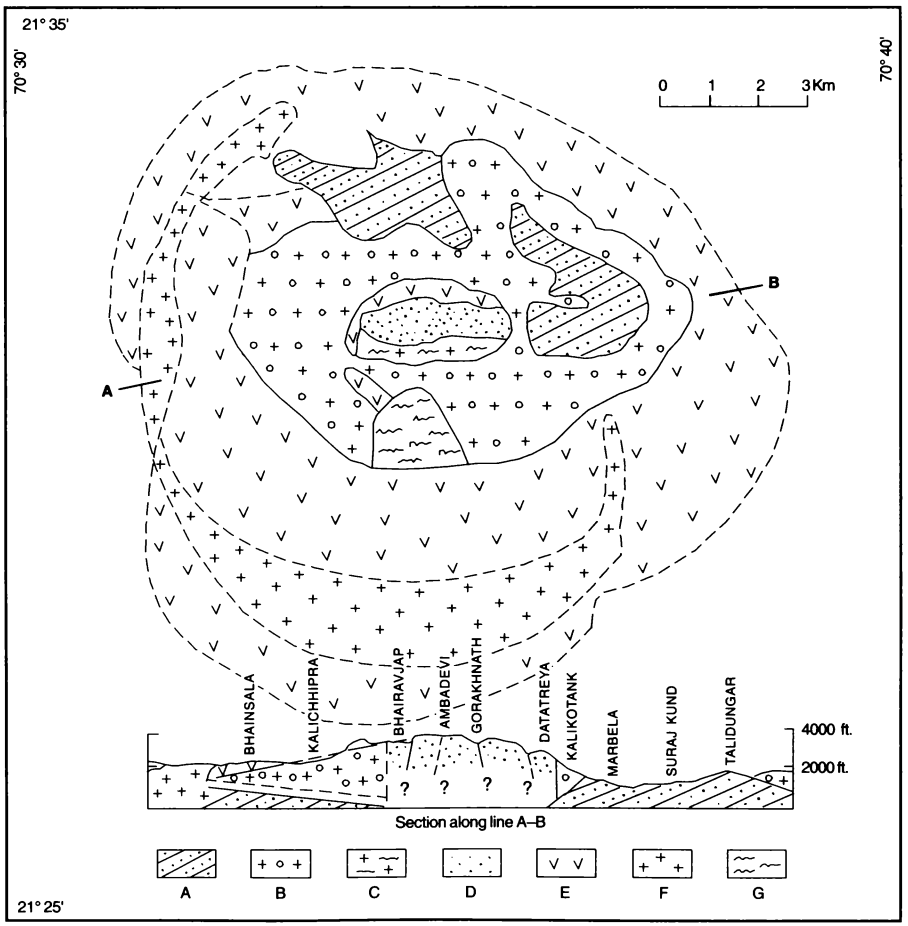


Fig.9.18. Geological map of Girnar Igneous Complex (after Chandra, 1995). A - Pyroxenite, B - Gabbro/layered gabbro, C - Biotite gabbro, D - Diorite/monzodiorite, E - Basalt, F - Microgranite and G - Alluvium.

and veins of nepheline syenite, limburgite, monchiquite, kersantite and comptonite. A number of dolerite dykes radiate from the complex.

5. Jetpur: A dome like body of felsic volcanics occurs near Jetpur.
6. Charmardi-Chowghat: An irregular mass of granophyre occurs to the north of Bhavnagar in the vicinity of Charmardi-Chowghat and Kadi.
7. Southern Saurashtra: A series of cuesta ridges of siliceous volcanics are exposed from Dhari to Palitana Hills. The ridges are composed of rhyolite, trachyte and pitchstone. Granophyre together with felsic tuff occurs in Sihor close to Bhavnagar. Near Loingdi, volcanic bombs of rhyolite embedded in obsidian indicate explosive volcanism. Undevitrified free glass is present in the siliceous volcanics near Kagvadar. Some of these felsic volcanics at Sihor, Rajula, Talaja etc. appear to mark the site of fissure eruptions.

B. Khambat Rift

1. Mundwara (12 sq.km; Fig.9.19) igneous complex consists of three distinct plutons (Toa, Mer and Musala), located near Mt. Abu in Rajasthan. There are two contrasting igneous units. The basic unit consists of essexite, melteigite and melasyenite. The felsic unit consists of felspathoidal syenite and syenodiorite. The intrusive plugs are riddled with radial and concentric dykes and carbonate veins along their margins. The different types of dykes suggest the derivation of alkaline members from sub-alkaline basaltic parentage.
2. Sarnu-Dandali: This alkaline complex consists of rhyolite, felsic tuff, alkali olivine basalt, hawaiite, trachyandesite, phonolite and melanephelinite. These are intruded by plugs of felspathoidal syenite and mafic-ultramafic alkaline rocks like melteigite and ijolite. Carbonatites (alvikite and ferrocarbonatite) intrude the Sarnu-Dandali complex as well as Barmer comendite.
3. Pavagadh Hill: This imposing hill near Vadodara (Baroda) exposes an ascending sequence of basalts, tuffs and rhyolites. Geochemical and petrological studies reveal a compositional spectrum from rhyolite, pumice, pitchstone to rhyodacite, basaltic andesite, mugearite, hawaiite, ankaramite and alkaline olivine basalt.

C. West Coast

1. Coastal tracts near Mumbai: Tholeiitic basalts are associated with andesite, trachyte, oceanite, ankaramite, monchiquite, rhyolite, rhyodacite and granophyre in Salsette and Bassein Islands as well as near Trombay,

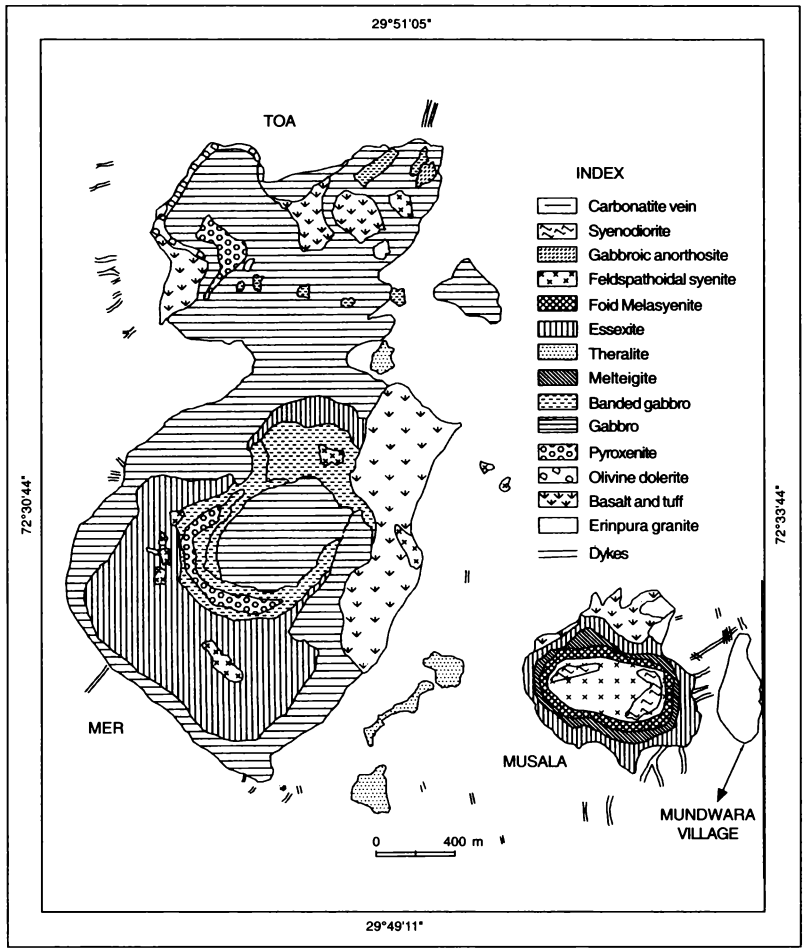


Fig.9.19. Geological map of Mundwara Igneous Complex (after T.R. Sharma, 1969 and N.P. Subrahmanyam, 1989 in Subrahmanyam and Leelanandam, 1989).

Worli, Jawahar, Malabar Hill etc. Some of the lamprophyres and nephelinites contain clinopyroxenite xenoliths of mantle origin, besides crustal xenoliths. Near Seoni and Bhoiwada near Mumbai, pillow lavas of spilitic composition are exposed (Fig.9.20). The spilites appear to have been derived from tholeiites through alteration under aqueous conditions. In Malabar Hills, a network of fine quartzofelspathic veins intrudes the tholeiites. The veins are made of quartz, orthoclase, adularia and fluorite. These are regarded as epithermal veins, which under favourable circumstances, host metallic minerals.

2. Murud-Janjira Alkaline Complex: It occurs along the West Coast about 6.5 km south of Mumbai, and consists of dykes of lamprophyre and nepheline syenite, plug-like elliptical bodies of ijolite and carbonated ijolite,

Fig.9.20. Pillow lava near Mumbai (courtesy: K.V. Subbarao).

Fig.9.21. Columnar jointed rhyodacite of St. Mary's Islands, off Malpe near Udupi on the west coast of Karnataka (Geol. Surv. India Spec. Publ. 61, 2001, p.35).

and breccia pipes containing clasts of granite, pyroxenite, ijolite and carbonatite. Alkali lamprophyre dykes enclose xenoliths of garnet-, two-pyroxene granulites, pyroxenites and felsic granulites that are derived from the deep crust of Western Dharwar craton (Dessai et al. 2004). The alkaline complex is intrusive into the basalts of Lonavala Subgroup, and is the second largest after the Amba Dungar Complex (Thorat, 2001).

3. St. Mary's Islands: A group of small islands off Malpe near Udipi exposes

spectacular columnar lavas of rhyolite and rhyodacite along with granophyre. These columnar lavas are declared as National Geological Monument in the Coconut Islands (Fig.9.21). Although these lavas are comparable to those of Salsette and Bassein in Mumbai, they are distinctly older (~90 Ma) than the DVP (~65 Ma) and have normal magnetic polarity. The St. Mary Island volcanics may signify the break-up of Madagascar from India at 90 Ma and may be related to Marion Hotspot.

D. Narmada Rift

1. Rajpipla: The area around Rajpipla, Netrang and Barwaha exposes alternations of tholeiite and alkaline basalts. Most flows are porphyritic basalts and trachybasalts. Several plugs of basalt, trachyte and potassic rhyolite intrude the lavas and are in turn intruded by tholeiite dykes. Two flows and several dykes of mugearite are also seen. Besides, a plug of fluorite-bearing carbonatite and many carbonatite dykes are also found.
2. Ambadongar (or Amba Dungar): The carbonatite-alkali complex (30 sq. km) forms a unique ring structure exposing several varieties of carbonatites and alkali rocks (Fig.9.22). Seven major units are recognised in the complex viz., carbonatite breccia, sovite, ankeritic and sideritic carbonatite, alvikite, silico-carbonatite and pegmatoid carbonatite

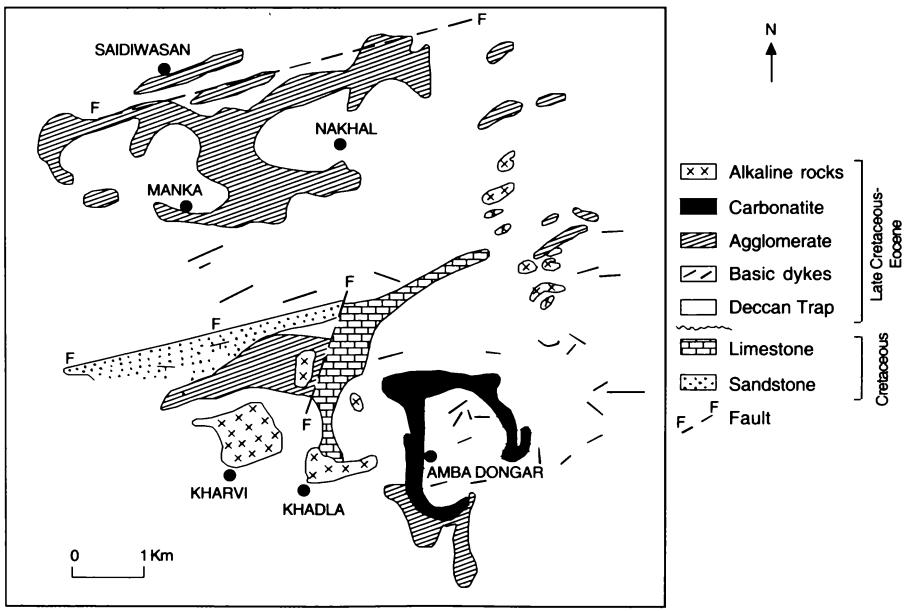


Fig.9.22. Simplified geological map of Amba Dongar alkaline carbonatite complex (after Viladkar, 1981).

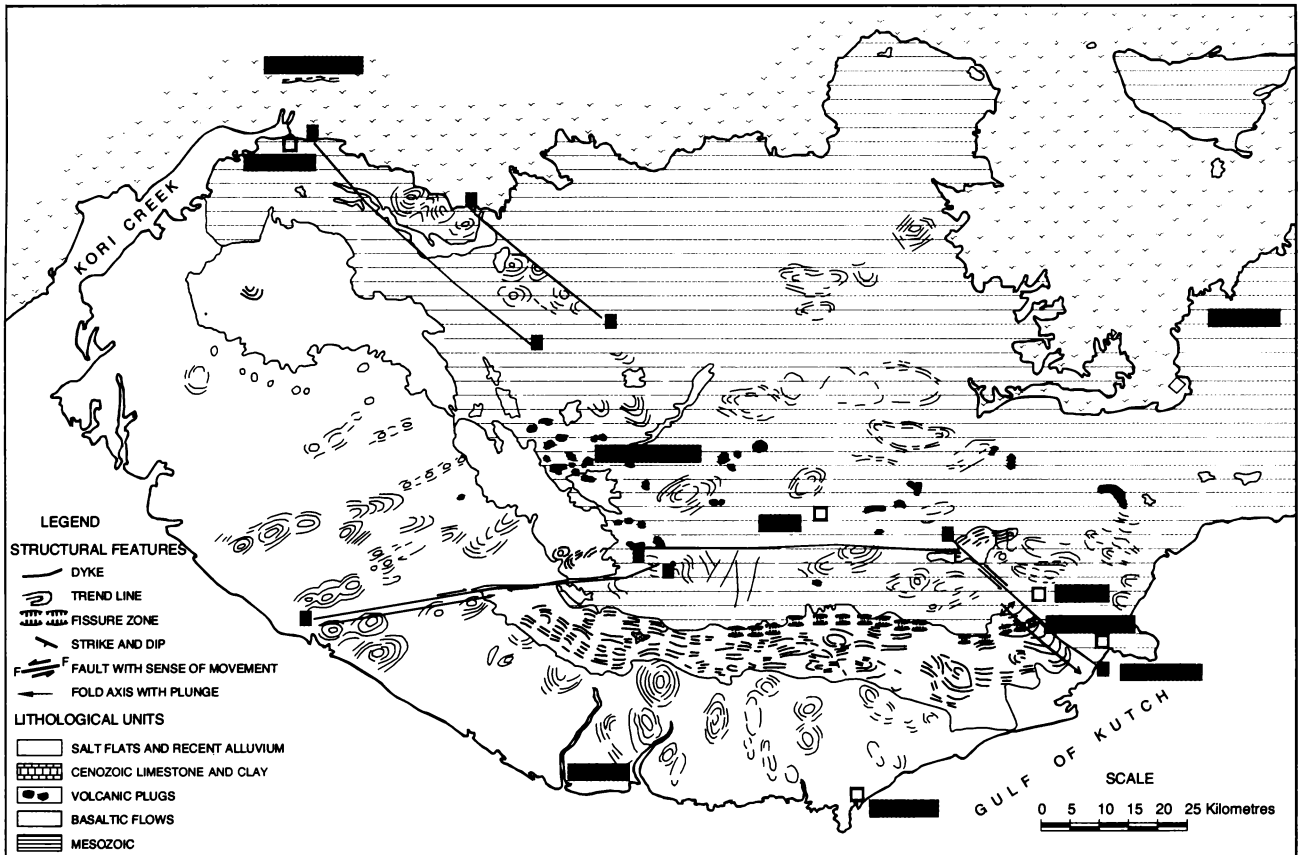


Fig.9.23. Deccan basalts and volcanic plugs of Kachchh (Misra, 1999).

(Srivastava, 1997). The carbonatites contain rich deposits of fluorite in the form of hydrothermal and replacement deposits in sovites and ferrocarbonatites. Trachytes are seen nearby in the Dugdha-Naswadi area.

3. Kawant: A variety of dykes and plugs of calcitic and dolomitic carbonatites surrounded by fenite and breccia zones is seen amidst tholeiites, alkaline basalts and picrites. Other dykes include syenite, nepheline syenite, phonolite, nephelinite, tinguaite, ijolite and lamprophyre. Tinguaite with pseudoleucite phenocrysts forms spectacular dykes.
4. Siriwasan: Dykes and sills of trachyte, carbonatite, tinguaite and phonolitic nephelinite occur in this area.
5. Phenai Mata (6 km^2): The composite volcanic plug of Phenai Mata has intruded the tholeiitic basalts near Chhota Udepur. The plug consists of layered gabbro intruded by granophyre. Other rock types are anorthosite, pyroxenite, diorite, monzogranite, microgranite and nepheline syenite (pulaskite).

E. Alkaline Rocks of Kachchh

The Deccan basalts occur in the form of a crescentic belt from Lakhpat to Anjar, trending NW to E and show pronounced layering and southerly dip (Fig.9.23). A linear fissure marked by fragmental siliceous volcanics extends to the west of Anjar. A significant feature of the Deccan Traps here is the presence of innumerable plugs, laccoliths and sheets of alkali basalt, mainly exposed around Nakhatrana, Nana, Drubia, Kala Dungar etc. The alkali basalts contain mantle nodules of spinel peridotite (lherzolite) and cognate xenoliths of dunite, clinopyroxenite and pyroxene granulite. Spinel peridotites contain olivine, orthopyroxene, clinopyroxene and spinel. The mantle sources of nodules and alkali basalts are apparently related genetically. Such mantle nodules occur in many continental basalt provinces of the world. These mantle nodules in Deccan Trap indicate steep geothermal gradients approaching the present day oceanic geotherm. The xenoliths provide evidence for the nature of Indian mantle at the time of Deccan volcanism.

F. Mafic Dyke Swarms

Dolerite dykes, mostly of tholeiitic composition, occur in two prominent swarms in the Deccan Volcanic Province viz., (1) Western Deccan Province and (2) Narmada Rift. In the central, south and eastern parts of Deccan Traps (Malwa, Mandla, Ajanta), dykes are not conspicuous, but occur as cross cutting, stellar, curvilinear and arcuate bodies with variable orientations (NE,

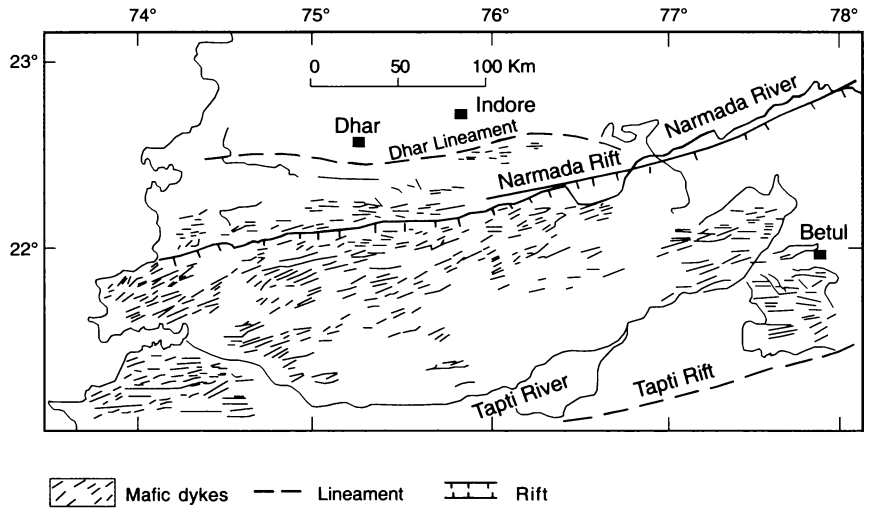


Fig.9.24. Mafic dykes in the Deccan basalts of Narmada valley (after Deshmukh and Sehgal, 1988; Bhattacharji et al. 1994).

NW, N etc). Ring dykes and radial dykes occur around intrusive complexes like Girnar. The dykes trend N-S to NNE-SSW and NNW-SSE in the Western Deccan Province and extensions are seen in Khambat graben. They trend E-W to WNW-ESE and ENE-WSW in the Narmada valley (Fig.9.24). In regional terms, the E-W trending dykes are older than the N-S trending types. Though tholeiites dominate, alkaline (trachyte, syenite, diorite), picritic and lamprophyric dykes are seen in the vicinity of alkaline and felsic volcano-plutonic complexes. Some chert-calcite veins prevalent in the area may denote silicification associated with faulting in the area.

The dykes are essentially linear but also occur in *en echelon* pattern. They are mainly of simple type, but at places composite and multiple dykes are also seen. In multiple dykes, they have multiple chilled margins and in the composite type they have variable composition of the constituents. Generally the dyke has sharp contact with host basalt, although the contact is locally indurated and reddened. There may be vertical layering, pinch-and-swell, silicification, offshoots and apophyses as well as bifurcation and reuniting features. Individual dykes are 100s of metres to 70 km long, and 0.5 to 100 m wide. The density of dykes is on the average 2 per sq.km with an average width of 15 m.

The dykes are uncommon in the upper horizons of Deccan Traps, which feature is attributed to greater fracturing of lower lava horizons. Dykes have high density of distribution in areas of extensive fracturing and flexuring (e.g. Panvel flexure) as well as in the Narmada and Khambat grabens and West Coast.

There is a popular concept that these dykes are feeders to the flood basalts (see Bhattacharji et al. 1994) and on this basis, several centres of eruptions have been identified, particularly in the West Coast. Dykes are filled fractures that represent linear vent systems. Some evidence of dykes passing into sills and thence into flows are recorded. The lack of correlation between intensity of dyking and topography has been advanced as an argument against the feeder dyke concept. A large number of dykes have, however, been shown to be post-Deccan Trap volcanism. In areas of dyke intensity, the dyke swarms are marked by positive gravity anomaly, thermal gradient, seismicity and horst-graben structures, which denote strong tectonic control of dyke emplacement.

Most dykes show textural variation from hypidiomorphic, subophitic to plagioclase phyric. They consist essentially of augite, pigeonite, olivine, calcic plagioclase, Fe-Ti oxides and apatite, along with Fe-hornblende, biotite and glass. Their chemistry indicates their similarity to N-MORB (Normal Mid-Ocean Ridge Basalt), with modification by crustal contamination (as evidenced by numerous siliceous xenoliths) to produce OIB (Ocean Island Basalt) compositions. The contamination of mantle-derived melt with the continental crust has been responsible for their varied compositions attained through AFC (assimilation with fractional crystallisation) or AEC (assimilation with equilibrium crystallisation). The mantle sources for these magmas are also regarded as heterogeneously enriched, the alkali basaltic magma having been generated at deeper levels.

PETROLOGY AND PETROGENESIS

Petrology

Tholeiites: Deccan basalts are mainly tholeiites consisting of clino-pyroxene, calcic plagioclase, olivine, magnetite, ilmenite, apatite and glass. Secondary minerals usually present are chlorophaeite, palagonite, iddingsite, zeolite, calcite and secondary silica. The basalts show a wide variation in texture like phyric, aphyric, subophitic, intergranular, intersertal and glomeroporphyritic (Fig.9.25 a to d). Most flows have 30% phenocrysts and in some varieties the percentage may go up to 50.

Ca-rich augite occurs in groundmass as microphenocrysts. Zoning, twinning and hourglass structure are sometimes seen. Pigeonite is limited to a few flows. Plagioclase (An_{58-68}) occurring in groundmass and as phenocrysts shows zoning and twinning. Olivine (Fo_{60-75}) mostly occurs as phenocrysts and is rarely present in the groundmass.

Picrites: Picrite basalts and picrites occur at the base of flows in Western

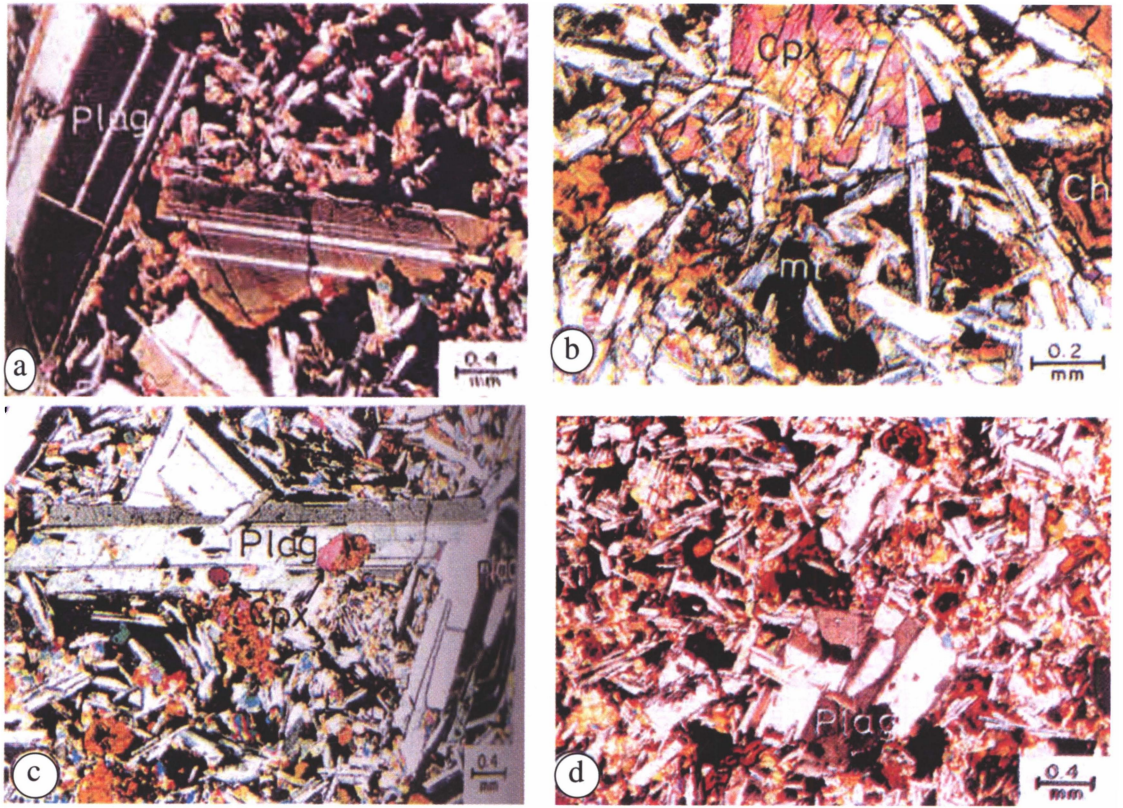


Fig.9.25. Common microscopic textures in Deccan basalts. (**a**) Plagioclase phyric basalt (Plag-Plagioclase). (**b**) Ophitic basalt. Plagioclase with laths of invading orthopyroxene (opx). Ch - chlorophaeite, mt - magnetite (**c**) Giant Plagioclase Basalt (GPB). (**d**) Glomeroporphyritic basalt with plagioclase (plag) as phenocrystic aggregates (Pattanayak and Shrivastava, 1999).

Ghats, Saurashtra and Kachchh. They consist essentially of highly magnesian olivine and pyroxene.

Alkali basalts: Alkali basalts occurring in Kachchh, Narmada rift and Cambay graben consist of wide variety of rock types rich in alkali minerals and felspathoids. The alkali basalts are mostly associated with felsic lavas and plugs. Melanephelinites, basanites and alkali basalts host spinel peridotite and cognate dunite nodules. The essential mineralogy of alkali basalts is olivine (Fo_{77-87}), diopside, salite, titan-augite, spinels (Mg, Cr and Ti-rich) and labradorite (An_{50-70}), sanidine and albite. Analcime, nepheline, perovskite, biotite and anomalous Ti-garnet are other minor phases. Among the mantle nodules, dunites are rich in olivine, which is close in composition to that in host basalts; spinel peridotites are rich in olivine, orthopyroxene, clinopyroxene and spinel.

Petrogenesis

Deccan Traps consist predominantly of quartz tholeiites with silica (48-52%), alumina (<15%), calcium (CaO 10-11%) and magnesia (5-10%). They are mainly enriched in iron (FeO 9-10%) and titanium (TiO_2 ~3%). Trace elements are variable but have a general coherence. Nd, Sr and Pb isotopes span a wide range. These are useful for correlation in unknown and far-flung areas and for petrogenetic interpretation. The Deccan tholeiites are petrogenetically evolved basalts and therefore represent derivative magmas.

The dominant tholeiites are products of fractionation of primary magnesian (picritic) magmas generated at ~1300° C and 10-15 kbar at shallow depths of 35 to 45 km. These picritic magmas are generated by the partial melting of MORB-type peridotitic mantle in the Indian Ocean at the K-T interval. The giant plagioclase basalts (GPBs), which are important stratigraphic markers, are derived from evolved magmas by felspar fractionation. The GPBs overlie red bole horizons during the dormant stage of magma fractionation. At the same time, olivine may have been precipitated to form picrite flows. The acidic and alkaline flows and intrusive complexes found in the Narmada and Khambat rifts are regarded as products of fractionation of basaltic magma contaminated with continental crust. The dominant role of either crustal contamination or enriched mantle source in the production of these differential flows and intrusions is a matter of on-going debate, with both sides presenting geochemical and isotopic evidence in their support.

Picrites: Another important lava type in Deccan basalts is the MgO-rich flows, namely, picrite basalts with MgO>10% and picrites with MgO>18%. Picrites and picritic basalts occur in several formations of Deccan Basalt/

Sahyadri Group in the Western Ghats, Saurashtra and Narmada rift. There is a controversy about their origin (Cox, 1999), namely, whether they are cumulates of tholeiitic magma or they are primary magmas derived from the mantle. The evidences in favour of primary origin are the quench textures, olivine compositions, thick picritic sequences in the basal parts of the flows and Mg/Fe ratios. However, the presence of abundant phenocrysts in picritic rocks favours crystal settling or fractionation. In order to explain this anomaly, some investigators have invoked modified fractionation models called 'compensated crystal settling' or 'delayed fractionation'. Another view is that the picrites of different areas in Deccan Traps are of different origins.

Alkaline lavas and intrusives: The next important lava type is the alkaline lavas in the Kachchh and Narmada rifts. Their petrogenesis is difficult to visualise because of absence of aphyric rocks that may indicate the original composition and the presence of xenoliths, xenocrysts and cognate nodules. These alkaline lavas (basanites and olivine nephelinites) appear to have been evolved in various stages. Polybaric fractionation of eclogite and pyroxenite is believed to have produced olivine mela-nephelinite or picrite liquid by partial melting of garnet peridotite source rocks. Polyphase fractionation of olivine, garnet, spinel, clinopyroxene and Fe-Ti oxides and mixing of primitive and evolved magmas and subcrustal contamination explain their complexity and genesis. Separation of immiscible carbonate liquid from alkaline magma explains the genesis of carbonatites. Further fractionation and loss of alkalies to the wall rock by fenitisation has led to development of fluorite and REE mineralisation.

AGE AND DURATION OF VOLCANISM

In the early years, K-Ar dating was widely used, which suggested a large span of volcanism from 30 to 100 Ma. Recent advancements in geochronology using $^{40}Ar/^{39}Ar$ and $^{187}Re/^{187}Os$ methods have shown a short span of Deccan volcanic activity from 63 to 68 Ma, a period approximately 5 to 6 Ma covering the magnetic chrons of 31R to 28N. Some dates of 60 Ma are recently reported, but their significance is yet to be evaluated. The alkaline lavas of Deccan are reported to have erupted within a period of ~2 Ma. Nannoplankton evidences indicate ~ 4 Ma duration of Deccan volcanism. These cumulative evidences have superseded the earlier notions of vast time span as well as the recent postulation of too short a period of ~1 Ma. Such a brief spurt of activity may be confined only to some parts as in the Western Ghats. The peak of volcanism is now reckoned at 65 to 66 Ma. These data are consistent with isotopic dating of many volcano-plutonic complexes in the DVP.

The age and duration of volcanism is important, as it is believed to have occurred close to K/T boundary, coinciding with mass scale faunal extinction and global climate change. Two current theories for such a catastrophe are: (i) extinction by bolide impact as proposed by Luis Alvarez, and (ii) extinction due to perturbation of carbon cycle by stupendous volcanic activity, as postulated by Dewey McLean. Though the Deccan volcanism seems to be closely related to the extinction of dinosaurs and other fauna, there is still a need to fine tune the data to obtain a holistic picture.

GEOPHYSICAL STUDIES

The Western Ghat and the West Coast are the most dynamic areas of the DVP with Khambat rift and its southern extensions witnessing the most intense volcanic activity during 60-70 Ma (Fig.9.26). The rift is marked by a thin crust of 33 km with Moho rising to 18-20 km further south near Billimora. Seismic tomography reveals a prominent low velocity region in the range of 40-200 km depth in the West Coast and this is probably related to zones of magma generation. Magnetotelluric (MT) studies reveal a MOHO depth of 30 km and lithospheric depth of 70 km in Valsad area. This region therefore presents

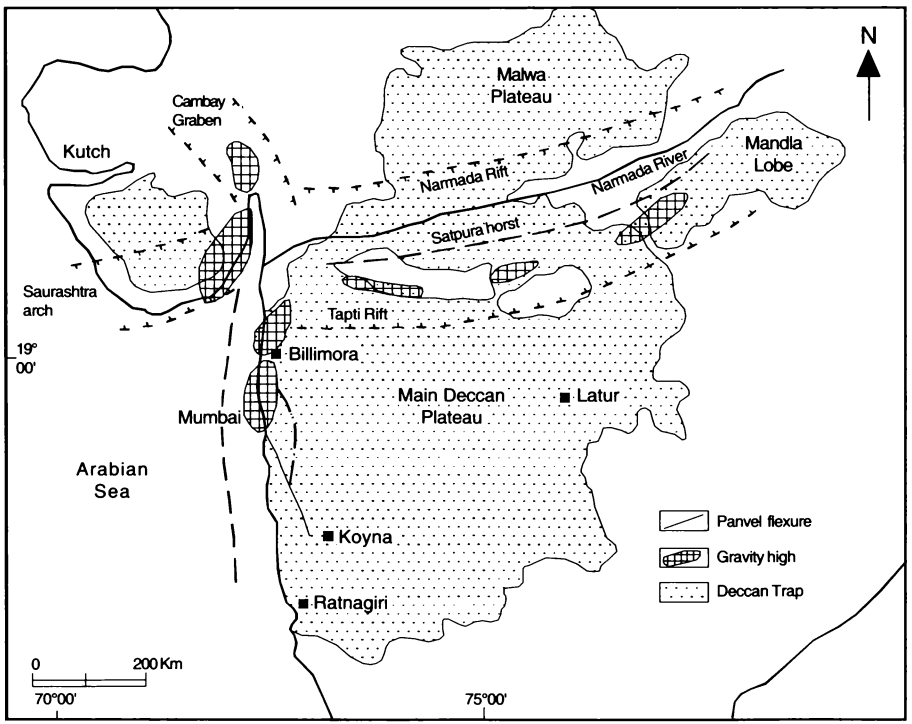


Fig.9.26. Distribution of rifts and gravity highs in DVP (after Kaila, 1988; Dessai, 2003).

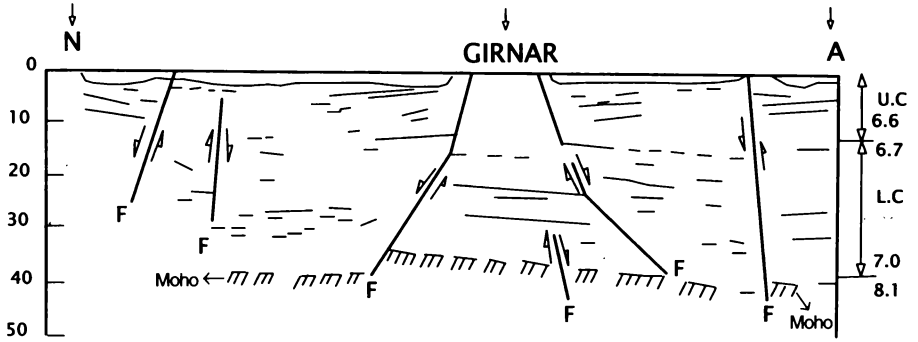


Fig.9.27. DSS profile across Saurashtra showing Girnar horst marking the site of Girnar Igneous Complex (after Kaila, 1988; Mahadevan and Subbarao, 1999).

evidences of asthenospheric upwelling along an active rift, possibly under the influence of the thermal plume, which is also manifested by numerous thermal springs in this belt.

The Saurashtra region is marked by a crust of 38-43 km thickness which is intruded by volcano-plutonic complexes which have a clear gravity signature. The DSS profile (Fig.9.27) shows the crustal structures in Saurashtra and the Girnar horst at the site of Girnar igneous complex. The SONATA belt is characterised by ENE-WSW trending horsts and grabens, as well as thick crust of 38-43 km depth. The crust is highly reflective which may be due to

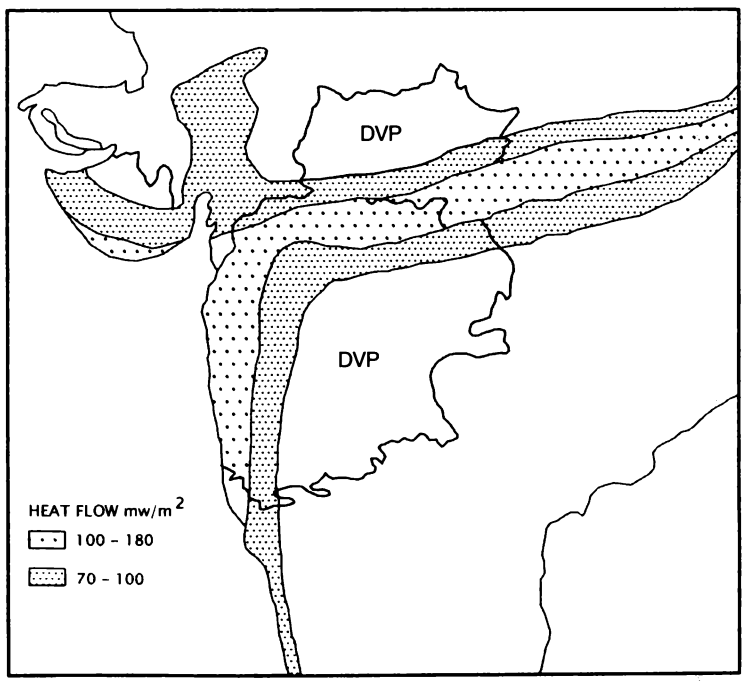


Fig.9.28. Heat flow values in DVP (after Ravi Shanker et al. 1996).

magmatic underplating or presence of fluid-enriched layers. Conductive zones seen near Jabalpur may be related to current seismogenic fractures.

The gravity field in the southeast region of the Main Deccan Plateau is negative (around –100 mgal) reflecting the presence of granitic basement. The heat flow values are low, similar to that of shield areas.

The heat flow values in the Western Ghats and West Coast, SONATA rift and Saurashtra range from 100 to 180 mWm^{-2} which is generally advective (Fig.9.28). Geothermal gradient of 14°C/km conforms to average shield geotherms.

STRUCTURE AND TECTONICS

Structure

Regional structure of DVP is difficult to decipher because of (i) different heights at which the same formations are exposed in various sub-provinces, (ii) frequent thinning and thickening of flows and (iii) prominent faulting in Western Ghats, Khambat graben and Narmada rift. Deep Seismic Sounding (DSS) studies have shown that the formations thicken broadly to the west as indicated by the isopach contour map (Fig.9.29). In the western Deccan Province,

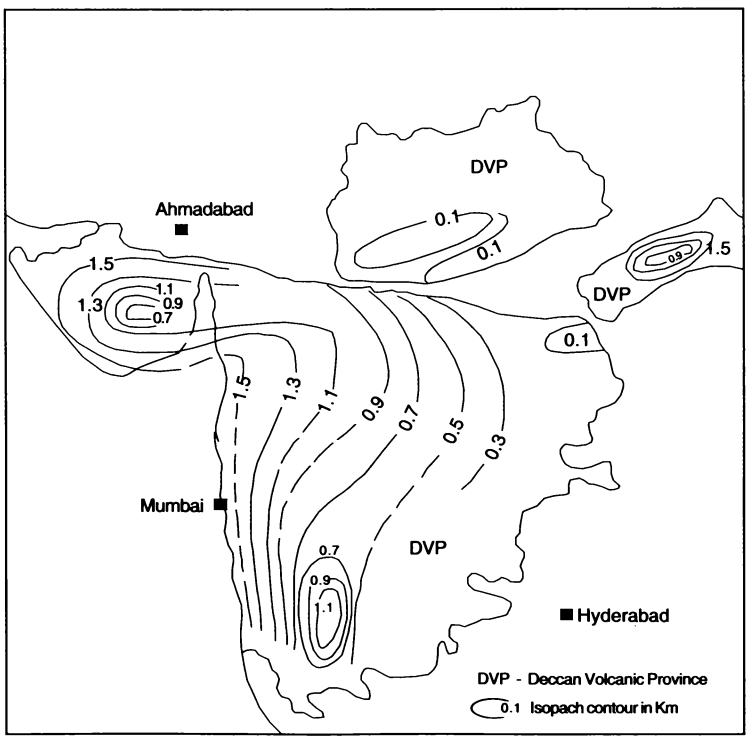


Fig.9.29. Isopach contour map of DVP based on DSS profiles (modified after Kaila, 1988).

regional dips of the flows suggest the presence of a major low amplitude, south-plunging anticline with a steeper western limb. The anticlinal axis roughly coincides with the crest of the Western Ghats. Faulting and folding related to the West Coast fault have caused the prominent Panvel flexure near Mumbai. Major N-S and E-W fault systems, related to the Khambat-West Coast and Narmada Rift respectively, are marked by closely spaced lineaments, dyke swarms and hot springs. Deccan lavas are also folded in the areas of disturbance. The Sonata (Son-Narmada-Tapti) lineament of the Narmada rift is regarded as an earlier feature, which is superposed by the presence of later N-S fault systems. Similarly, the embayment between Saurashtra and Kachchh is marked by the Kachchh rift. These faults bounding the rifts have generated the Saurashtra and Satpura horsts.

Tectonics

Continental Flood Basalts (CFBs) are believed to be the products of plume activity in the mantle (Fig.9.30), although dissenting views also exist (Sheth, 2005). Deccan Traps may have originated when India drifted northwards from Antarctica towards Asia, riding over the Reunion Plume or Hotspot (Fig.9.31). The size of the plume head that caused Deccan volcanism is believed to be of large (~800-2500 km) diameter. These events are related to the supercontinent break up and dispersal of Gondwana. The non-plume model visualizes rifting due to large scale plate dynamics aided by long term thermal insulation beneath a supercontinent.

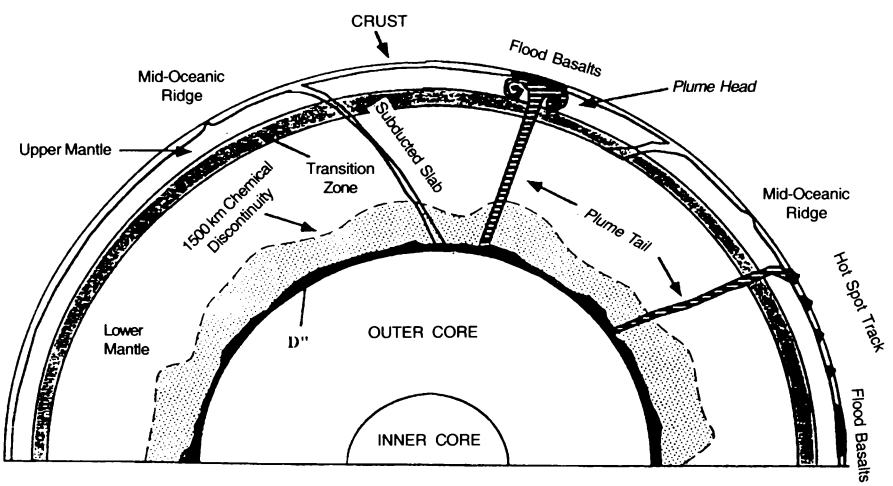


Fig.9.30. Origin of large plumes from core-mantle boundary. Plume heads melt to produce flood basalts. Plume tails generate hot spot tracks (after Sen and Cohen, 2001)

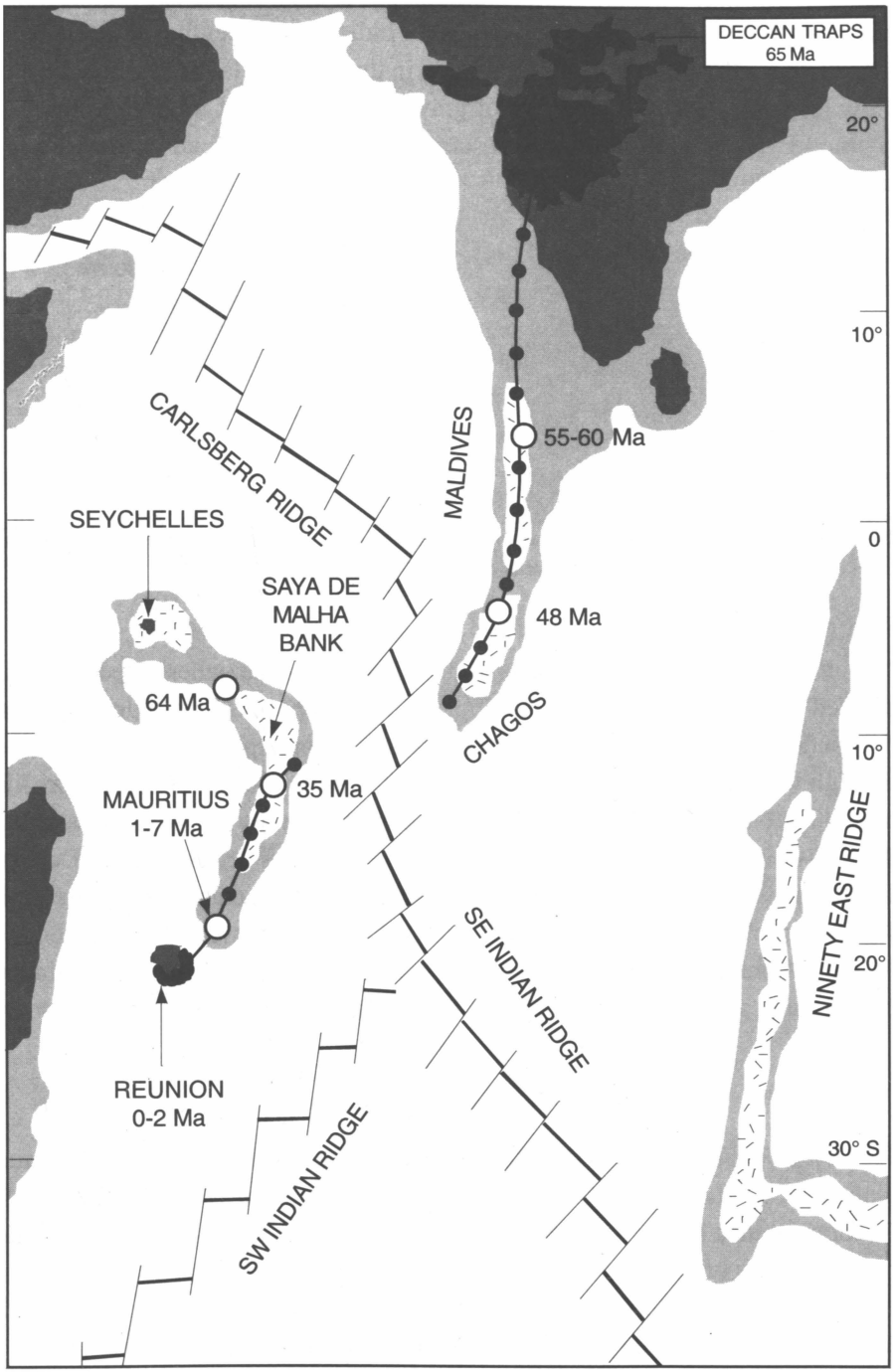


Fig.9.31. Movement of India over the Reunion plume (Subbarao et al. 2005).

The Deccan lavas are believed to have erupted from a volcanic centre in the western part of DVP (*see* Sethna, 2004). The centre appears to have migrated to the south with the movement of Indian plate over the plume, leaving a north to south plume trail. The variation in thickness of lavas, regional dips of flow (Fig.9.32) and the presence of gravity highs support migration over the plume. Evidences of vents, fissures and feeder dykes abound in the volcanic centre.

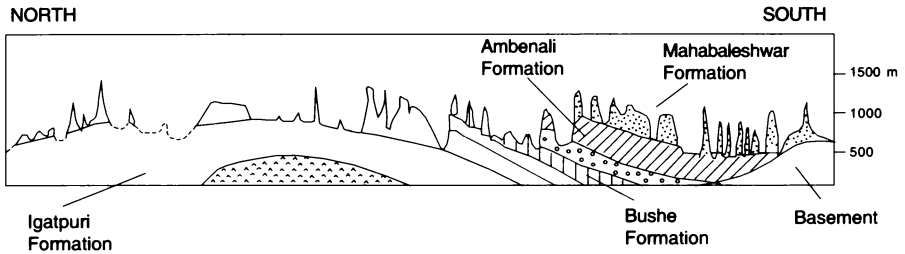


Fig.9.32. Regional dips of Deccan lavas support doming due to underplating of magmas forming large magma chambers (Subbarao et al. 1994).

It is believed that the volcanism is triggered by the underplated magmas ponded in large magma chambers (Fig.9.32). The impact of the plume head on the continent has probably caused the underplating. Underplating is also supported by high velocity (7.3 to 7.4) at shallow levels (10-20 km) in the seismic profile across the Narmada Rift, which is also a zone of gravity high. There is still a debate whether doming and crustal stretching occurred before or after Deccan volcanism. Similarly there are many related problems demanding our attention such as mechanism of plateau uplift, role of epeirogeny and development of easterly drainage in the Indian Peninsula (with the exception of westerly drainage of Narmada and Tapti Rivers caused by Narmada Rift).

ECONOMIC MINERALS

Flood basalts are known to host important deposits of native copper and platinoids. Epithermal gold and gold-silver deposits are also known elsewhere. Reconnaissance studies on Deccan Traps have not found any indicators of the mineralisation of this type. Bauxite cappings over Deccan Trap as in Belgaum are useful as aluminium ore. Natural zeolites filling the cavities in volcanics are useful as gemstones and have industrial and agricultural applications.

INTER-TRAPPEAN BEDS

INTRODUCTION

The Deccan Trap, in different parts of India, covers many of the older formations, like the Precambrian (Archaean and Proterozoic), Gondwana and Cretaceous formations in parts of Central and Western India. Before the advent of radiometric dating, the age of the Deccan Trap was invariably fixed based on the age of the youngest underlying fossiliferous formations, mostly of Cretaceous age, designated as Infra-trappean beds, and ages obtained for the youngest Inter-trappean beds. It was soon noted that there are such fossiliferous horizons in different places (Fig.9.33) at different levels in different sections of the Deccan Traps and they may be infra-, inter- or supra-trappean beds (Fig.9.34). The same horizon may be infra-trappean in one place and inter-trappean in another. There are numerous localities in India where these have been studied in detail for their lithological and faunistic contents, mainly on land and a few from offshore boreholes as well.

Study of the fossils and the rocks of the infra- and inter-trappean beds goes back to almost the beginning of the nineteenth century, not necessarily by geologists, but by dedicated naturalists. Plant fossils were reported from Sagar in Madhya Pradesh, by Coulthard in 1829 and Hislop and Hunter in 1855. Birbal Sahni studied them in detail in 1931 and also subsequently reported fossil fungi from the Deccan inter-trappean beds. A chert collected from the Mohgaonkalan inter-trappean beds in Madhya Pradesh, yielded twelve Deuteromycetan fungal forms belonging to *Hypomycetes.* Similarly, Hislop and Hunter in 1855, Blanford in 1867 and Hora in 1938 reported vertebrate fossils. Some ostracodes, radiolarians and foraminifera are also reported from time to time from surface as well as infra- and inter-trappean sediments in subsurface.

DISTRIBUTION

The nature, fauna and flora of some of the infra- and inter-trappean beds are described below along with their significance.

Anjar

The Anjar volcano-sedimentary sequence in Kachchh comprises as many as seven basaltic flows enclosing four inter-trappean beds. They are about 5 m thick and contain dinosaurian fossils. Iridium concentration (about 1200 pg/g) has been detected in the third inter-trappean bed. Lithologs of the pits show

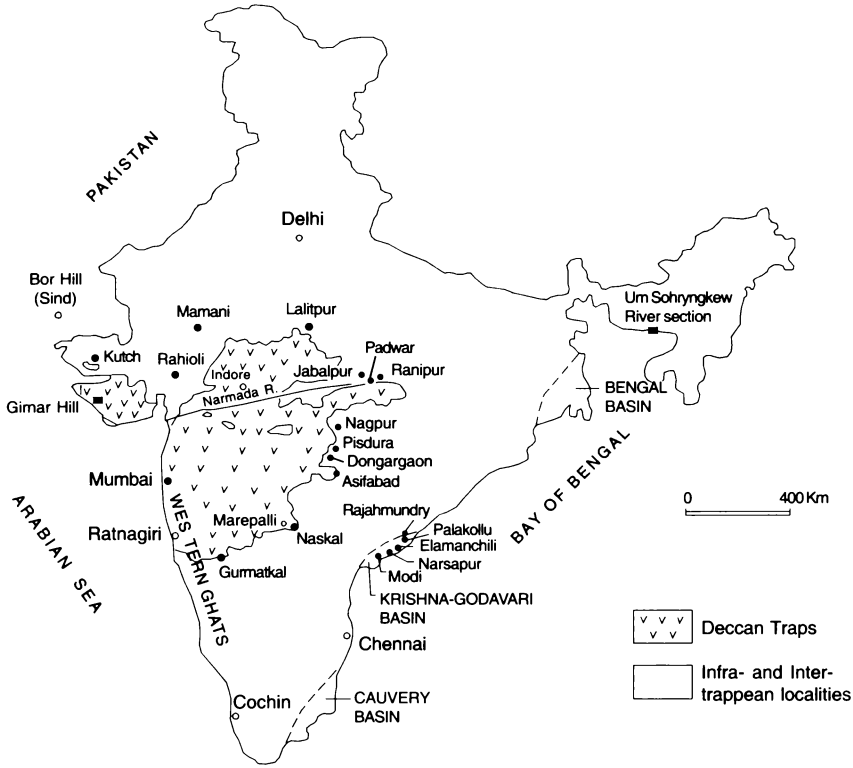


Fig.9.33. Map showing the distribution of infra- and inter-trappean beds in peninsular India (after Prasad and Khajuria, 1995).

limestone, grey shale, brown shale, basalt, shell hash (broken debris), chert and mudstone with basalt clasts. The shell hash is mostly made up of molluscs, some ostracodes and dinosaurian remains. Abundant bioclasts, bedded nature and peloids suggest that the limestones in which they occur were formed in the littoral zone of a lake – an ancient alkaline lake. High carbonate content

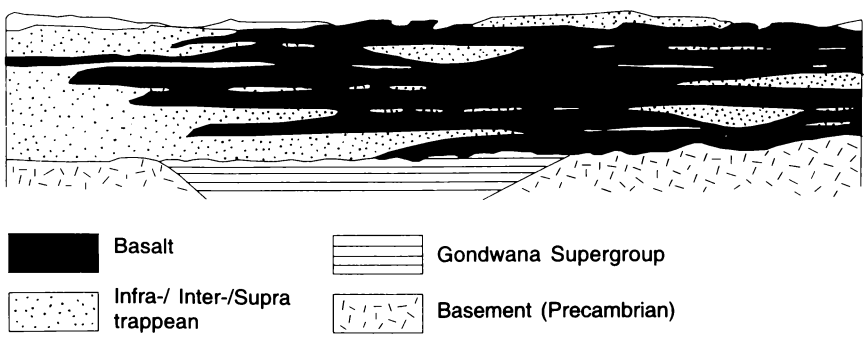


Fig.9.34. Schematic representation of possible relationships between infra- and inter-trappean sequences and the associated lava flows and the rifted basement lithologies (after Tandon, 2002).

of the sequence suggests prevalence of semiarid conditions. Limb bones, vertebrate claws, coprolites and skins of dinosaurs are described pointing to a possible habitation of sauropods and theropods in the area. Violent central type of explosion in the vicinity is considered to have caused their extinction.

Mumbai (Bombay)

Basaltic lava flows separated by thick inter-trappean sediments can be observed both in the western ridge of Malabar, Cumballi and Worli Hills and the eastern ridge of Antop, Sewri, Bhoiwada and Cotton Green Hills. The greenish ash bed, black and thinly laminated shales and yellowish fine-grained bedded tuff material occur below the hyalopilitic basalt of the western ridge. The black discontinuous shaly material is fossiliferous in patches.

Frogs (*Indobatrachus pusillus*), fresh water tortoises (*Carteremys leithii*), cyprids, insects, and a fish tooth, were obtained from the black shales of Worli Hill. The fossil content of black shale suggests the environment of deposition to be stagnating bodies of fresh water. In some of the sections of inter-trappean beds, ostracodes occur –*Mongolianella* – *Altanicypris* – *Cypridea* – *Timiriaservia* – *Cyprois*, an assemblage which is comparable to other Deccan volcano-sedimentary sequences in Jabalpur, Mamoni, Nagpur, Asifabad and Gurmatkal.

In Mumbai, the inter-trappean beds appear to be closer to volcanic sources as pyroclastics predominate, unlike those along the fringe of Deccan Trap, where the volcanics lie over Gondwana or Precambrian formations.

Naskal

A new eutherian (therian=beast) mammal is reported from the uppermost Maastrichtian sediments intercalated in a volcanic sequence in Naskal, Pargi taluk, Ranga Reddi district, Andhra Pradesh. The first record of a Laurasian mammal indicates wide distribution of these creatures and according to some suggests that the Indian plate was perhaps not isolated from northern continents despite the geological evidence. Mammalian teeth were recovered along with remains of other vertebrates (fish, frogs, lizards, snakes, turtles and crocodiles) from pinkish white sandy marl of the inter-trappean succession exposed 2 km northeast of the village of Naskal.

Jabalpur

Microfossils recorded from here suggest belonging to Lameta (p.720) fluvial environment of deposition for the sediments. Based on the occurrence of

a common clay mineral assemblage (montmorillonite, chlorite and illite) in the infra-trappean bed as well as the basal volcanic flows overlying the infra-trappean beds of Jabalpur, the infra-trappean beds are supposed to have been deposited either synchronously with or after the initiation of volcanic activity. The Maastrichtian fishes *Igdabatis* and *Rhombodue* are known from infra-trappean beds of Jabalpur.

Dicot and monocot leaves along with some wood remains are reported from near Deccan inter-trappean fossiliferous localities situated in the Seoni and Mandla districts of Madhya Pradesh. The leaf remains belong to *Dictyophyllum saporta, Phoenicites brongniart, Amesoneuron goeppert* and the woods are represented by *Hydnocarpoxylon bande & khatri, Polyalthioxylon bande*, and *Palmoxylon schenk* (Maastrichtian-Paleocene).

Rajasthan

Intertrappean beds of southeastern Rajasthan are the westerly extension of their counterparts in Madhya Pradesh. Two widely separated fossiliferous intertrappeans are exposed near Narli, south of Jalarpatan, Jhalawar district, and Mamoni in Kota district. They have yielded fresh water ostracodes, which include *Cypris hunteri, Moenocypris, Mangolianella, Pseudoeucypris, Paracypretta.*

Asifabad and Nagpur

An ostrocode assemblage represented by *Talicypridea, Atlanticypris, Cypridea, Candona* and *Mangolianella* is reported from the inter-trappean beds of Asifabad and Nagpur. A similar assemblage has also been recorded from the inter-trappean beds of Mamoni, Rajasthan and Gurmatkal, Karnataka. The palynofossils reported from these areas include *Azolla cretacea, Gabonisporis vigourouxii, Aquilapollenites bengalensis, Triporoletes reticulates, Hemicorpus, Equisetosporites* – all referable to Maastrichtian.

Rajahmundry

Foraminiferal assemblages recorded from the infra-trappean beds beneath Rajahmundry basal flows, obtained from borehole data, are as follows:

Abathomphalus mayaroensis, Globotruncana arca, G. stuarti, Pseudotextularia elegans, Racemiguembelina fructicosa, Globotruncanella citae, Rugoglobigerina rugosa.

Sixteen ostracode taxa are recorded from the exposed inter-trappean beds near Duddukuru. The following *Cushmanidea bhatiai, Cytherella mohani, Cytheridella rajahmundryensis* and *Palmoconcha rajuvi* are new. Fossil assemblages in the inter-trappean sediments in Rajahmundry lavas indicate that volcanic eruptions took place in a coastal environment, towards the end of the

Cretaceous. The Rajahmundry lavas have been dated at c.64 Ma based on $^{40}Ar/^{39}Ar$ method.

Narasapur

In the Narasapur-1 well in Godavari delta, the basal flows overlie infra-trappean beds bearing the planktonic foraminifera *Abathomphalus mayaroensis*, which indicates that the basal flows are no older than Maastrichtian. This is also true of the Palakollu–A, Elamanchali-A and Modi-A wells (Table 9.4), which have yielded planktonic foraminiferal assemblages corresponding to the *Abathomphalus mayaroensis* zone.

Table 9.5 gives a list of most of the fossils identified in the different inter-trappean outcrops in the country.

PALEOBIOGEOGRAPHY

Affinity of the Late Cretaceous infra-trappean vertebrates, such as pelomedusid turtles and abelisaurid dinosaurs lies with those of Gondwana landmasses. It seems more likely that these taxa are relicts of the Gondwana stock that boarded the Indian plate well before its separation from Madagascar 70-80 Ma ago. Remnants of former Gondwanaland fauna, such as pelomedusid turtles and leptodactylid frogs did persist in relatively younger (latest Cretaceous) inter-trappean beds. In addition to these Gondwana elements, the inter-trappean beds register many North American, European and Central Asiatic taxa (pelobatid and discoglossid frogs, anguid lizards, alligatorid crocodiles, eutherian mammals, a few ostracode species and charophytes) suggesting that by the end of Cretaceous a contact between India and Southern Asia was established. The pandemic nature and Laurasiatic affinities of vertebrate faunas from the inter-trappean beds point to a close proximity of the Indian subcontinent and Eurasiatic continent, suggesting possible biotic dispersals across island arcs close to K/T boundary.

AGE

Many theories have been proposed for the mass scale extinctions of fauna approximately around the K/T boundary. Interestingly enough the study of magnetic reversals vis-à-vis marine animal diversity shows that there has been a considerable reduction in the number of magnetic reversals at the P/T and K/T boundaries. Deccan Trap volcanism may have covered no more than three polarity intervals, one reversed sequence between two normal ones.

The assemblage of dinosaurs and fishes besides others in Anjar inter-

trappean beds suggests a Late Cretaceous (Maastrichtian) age based on correlation with similarly dated dinosaur bearing inter-trappean beds of western Kutch, Nagpur, Asifabad and Jabalpur. The basalts below and above the inter-trappean beds in Anjar gave ages approximately 65.2±0.6 Ma and 65.7±0.7 Ma respectively by $^{40}Ar/^{39}Ar$ method. The assemblage recovered from the Ranipur inter-trappean beds exposed in the Gaur River in the Jabalpur area is assignable to Maastrichtian. The foraminiferal assemblage in Rajahmundry area is assigned Late Maastrichtian to early Paleocene. Biostratigraphically significant palynofossils were recovered from the inter-trappean beds of Padwar near Jabalpur in Madhya Pradesh and Naskal in Andhra Pradesh indicating a Maastrichtian age.

All inter-trappean dinosaur levels fall within the reversed palaeomagnetic interval and overlie basalts dated 66.2±3.9 Ma (Dongargaon) and 61.7±5.0 Ma (Nagpur). Moreover, the Eurasian character of the K/T boundary terrestrial faunas in India suggests that this period was also close to the time of India-Asia collision.

Some of the recent studies indicate that the presence of *Lepidotus*, *Meagalosaurus*, symmetrodont mammal and *Platychara perlata* from the Takli Formation, Nagpur suggest a Late Cretaceous age for the Takli Formation. The absence of any dinosaurian remains, *Lepidotes*, *Rhombodus* (which are typical Late Cretaceous elements) and presence of *Alloganthosuchus, Asiatosuchus* (not found before the Paleocene), *Notopterus, Osteoglossum, Scleropages, Heterotis* and *Nemegti chara* from the Naskal and Rangapur, Chimalgutta and Mallangutta though suggested to represent the Early Paleocene age, it is debatable.

Micropalaeontological investigation of an iridium-bearing, lacustrine inter-trappean sedimentary sequence at Anjar has revealed a profuse occurrence of theropod eggshell fragments (ornithoid type) in beds overlying iridium-enriched levels. Associated Late Cretaceous ostracodes lack evidence of reworking. The absence of any exclusively Paleocene taxa above the iridium levels, taken together, indicate that the extinction of dinosaurs in the Indian subcontinent occurred after the deposition of iridium layers at Anjar, and that these iridium anomalies may significantly predate the K/T boundary. The extinction of dinosaurs does not coincide with any of the iridium levels in the Anjar inter-trappean beds. The iridium is interpreted as a consequence of bolide (an exploding or exploded meteor or meteorite) impact unrelated to the Deccan volcanism.

In conclusion, the palaeontological data suggest a Late Maastrichtian initiation of the Deccan volcanism at the top of the *Abathomphalus mayaroensis* planktonic foraminiferal zone (66.5 Ma) and an Early Paleocene termination at the base of *Globorotalia (A) praecursoria carinata* zone (61.2.0 Ma).

Table 9.4. Biota of subsurface Inter- and Infratrappean localities in Krishna-Godavari Basin (*pers. comm.* G.V.R. Prasad)

Biota	Intertrappean					Infratrappean					
	Chintalapalli - A	Elamanchili - A	Modi - A	Narsapur Well- 1	Palakollu - A	Chintalapalli - A	Elamanchili - A	Modi - A	Narsapur Well -1	Palakollu - A	Razole - A
Forminifera:											
Abathomphalus mayaroensis				x		x		x	x	x	x
Anomalinoides rubiginosa					x						
Anomalinoides acutus				x							
Anomalinoides subiginosa					x						
Archaeoglobigerina blowii										x	
Bathysiphon sp.				x							
Boldia sp.					x						
Bulimina arkadelphiana										x	
Bulimina spinata										x	
Ceratobulimina cretacea				x							
Clavulinoides disjuncta										x	
Cribrostomoides cretaceus				x						x	
Cribrostomoides cf. *cretaceus*				x							
Dorothia minutula					x						
Dorothia oxycona					x		x				
Eoglobigerina eobulloides					x						
Eoglobigerina trivialis					x						
Gaudryina bronni					x		x				
G. laevigata										x	
Gansserina wiedenmayeri										x	
Globorotalia compressa					x						
Globorotalia (T.) pseudobulloides					x						
Globorotalia (Turborotalia) sabina					x						
Globotruncana sp.	x									x	
Globtruncana arca	x								x		
Globotruncata aegyptica										x	
Globotruncata conica										x	
Globotruncana gagnebini				x					x		
Globotruncanella petalloidea										x	
G(Acarinina) praecursoria praecursoria					x						
G. (T) compressa					x						
G. (T.) cf. *imitata*					x						
Globotruncana stuarti			x	x			x		x	x	
Globotruncana stuartiformis							x		x	x	
Guembelitria cretacea					x					x	
Hecemiguembelina fructicosa										x	
Heterohelix striata									x		
Lenticulina daviesi				x							
Lenticulina cf. *daviesi*				x							
L. muensteri				x							
Neobulimina reussi				x							
Nodellum velascoensis									x		
Neoflabellina permutata									x		
Pelosina complanata				x							
Planoglobulina		x									
Praebulimina corsayae										x	
Pseudotextularia browni				x					x		
Racemiguembelina fructicosa									x		
Reophax texanus				x							
Rugoglobigerina rugosa									x		
Rugoglobigerina scotti									x		
Tappanina selmensis									x		
Ventilobrella sp.									x		
Calcareous Nanoplankton:											
Arkhangelskiella sp.											x
Cyclagelosphaera reinhardtii											x
Micula decussata											x
Micula murus											x
Prediscosphaera cretacea											x
Prediscosphaera spinosa											x
Stradneria crenulata											x
Watznaueria barnesae											x

Summary of Late Cretaceous Paleobiogeography

Application of bulk screen-washing techniques on the Deccan infra- and intertrappean beds have resulted in the recovery of many new taxa previously unknown to the scientific world and has substantially improved the fossil record of these volcano-sedimentary sequences in the last decade. The most important findings from these beds are the discoveries of first defenitive Late Cretaceous ungulate-like (hoofed) mammal (*Kharmerungulatum vanvaleni*), a new species of *Deccanolestes* (*D. narmadensis*) with close phylogenetic relationships to Late Paleocene adapisoriculids from Africa (*Afrodon chleuhi*) and Europe (*A. germanicus*), new high-crowned mammal of sudamericid gondwanathere affinity (*Bharattherium bonapartei*), a partially preserved skeleton of madtsoid snake associated with a clutch of titanosaurid egg clutch and hatching, oldest grasses from titanosaurid coprolites, and oldest freshwater diatoms.

Contrary to the anticipated development of purely endemic fauna and flora on northward drifting Indian plate, the biota from these sedimentary beds is represented by an admixture of Gondwana, Laurasian, and endemic elements. Based on the occurrence of typical Gondwanan gondwanathere mammals, leptodactylid frogs, pelomedusoid turtles, mesosuchian crocodiles, and nigerophiid snakes, a Late Cretaceous terrestrial connection between Indo-Madagascar and South America across Antarctica and Kerguelen Plateau or Gunnerus Ridge was visualized. Recent geological and geophysical evidences from the Indian ocean, which have shown the Kerguelen Plateau submerged below the sea level during the Late Cretaceous, have however questioned this model. On the other hand, the Laurasiatic affinity of eutherian mammals (including *Kharmerungulatum*), anguimorph lizards, discoglossid frogs, pelobatid frogs, and charophytes, led to the suggestion that these small-sized animals and plant remains may have dispersed across Kohistan and Dras island-arc systems by sweepstakes mode of dispersal. In contrast, the ostracode fauna is of highly endemic at species level though predominantly Laurasian at generic level. Recent molecular phylogenetic studies have predicted that many living Southeast Asiatic biotic elements had actually originated on the former Gondwanaland (Africa, South America, Antarctica, Australia, New Zealand, Madagascar, India) continents and were ferried to Southeast Asia across drifting India. This has been designated as "out of India dispersal" hypothesis. The discoveries of *Lagerstroemia* plants and ranoid frog remains from the Deccan intertrappean beds lent some credence to this hypothesis. It has also been speculated that India was a centre of origin for many animal and plant groups during its northward flight as the oldest ungulate-like (*Kharmerungulatum*) mammal, earliest eutherian mammal representing the basal stock of Euarchonta (that includes primates, tree shrews, and flying lemurs), oldest grasses and oldest freshwater diatoms are known from the Late Cretaceous Deccan intertrappean beds.

Table 9.5. Fossiliferous Deccan Inter-trappean outcrops (*pers. comm.* G.V.R. Prasad)

Biota	Andhra Pradesh				Gujarat				Karnataka				Madhya Pradesh					Maha-rashtra		Rajas than	Uttar Pradesh
	Asifadad	Rajahmundry	Naskal	Rangapur	Anjar	Bamanbor	Kora	Lakshmipur	Biligi	Gurmatkal	Upparhatti	Yellur	Kisalpuri	Mohgaon-Kalan	Padwar/Ranipur	Mandla	Sagar	Bombay	Nagpur	Mamoni	Lalitpur
Gastropods: -																					
Physa prinsepii		x			x		x	x	x	x	x				x	x	x		x		
Lymnaea sp.		x					x	x	x	x	x					x	x				
Viviparus sp.										x	x						x				
Paludina sp.		x			x			x		x	x					x	x				
Bivalves: -																					
Unio deccanensis									x	x	x					x					
Ostracodes: -																					
Altanicypris deccanensis								x													
Bairdia subdeltoidea		x																			
Bairdia krithe		x																			
Bythocypris ? sp.		x																			
Candona amosi					x		x			x											
Candona mysorephaseolus										x											
Cushmanidea bhatiai		x																			
Cyclocypris sahnii							x								x						
Cyclocypris amphibolos							x				x										
Cypria cyrtonidion							x	x		x				x					x		
Cypridopsis astralos								x													
Cypridopsis elachistos														x							
Cypridopsis hyperectyphos							x	x		x											
Cypridopsis legitima								x													
Cypridopsis wynnei								x		x									x		
Cypris semimarginata																		x			
Cypris cylindrica																		x			
Cytherelloidea sp. cf. *C. keiji*		x																			
Cytherella mohani		x																			
Cytheridella strangulata	x																		x	x	
Cytheridella rajahmundryensis		x																			
Darwinula torpedo										x											
Eucandona kakamorpha										x											
Frambocythere tumiensis anjarensis					x					x											
Gomphocythere akalypton										x											
Gomphocythere dasyderma										x											
Gomphocythere strangulata										x											
Gomphocythere paucisulcatus														x							
Eucypris intervolcanus							x	x		x				x							
Eucypris pelasgicos							x	x						x					x		
Hermanites sp.		x					x														
Hermanites sastryi		x																			
Hornibrookella tewarii		x																			
Linmocypridea eephymatos					x		x														
Mongolianella cylindrica							x	x		x											
Nucleolina diluta		x																			
Ovocytheridea raoi		x																			
Protobuntonia hartmani		x																			
Paracypretta bhatiai	x				x		x			x			x	x							
Paracypretta elizabethae							x	x		x											
Paracypretta jonesi										x									x		
Palmoconcha raju		x																			
Paracandona jabalpurensis													x								
Protobuntonia hartmanni		x																			
Xestoleberis sp.		x																			
Zonocypris spirula							x	x		x											
Foraminfers: -																					
Anomalina rudio		x																			
Globorotalia cf. *G. menardii*		x																			
Globotruncana sp.		x																			
Guembelina globifera		x																			
Nodosaria zippei		x																			
Nonion sp. indet.		x																			
Orbulina cf. *O. universa*		x																			
Robulus sp. indet.		x																			
Robulus cf. *occidentalis*		x																			
Spheroidinella sp.		x																			
Triloculina cf. *laevigata*		x																			
Charophytes: -																					
Chara sp.							x			x											
Grambastichara sp.										x											
Gyrogonites medicaginula									x	x											
Platychara perlata	x			x			x			x									x		
Platychara compressa							x			x											
Platychara rajamundrica		x					x														
Platychara raoi							x			x											
Platychara sahnii		x					x			x									x		
Peckichara varians							x			x									x		
Harrisichara muricata							x			x											
Nemegtichara grambasti				x			x			x										x	
Microchara sp.										x											
Pseudoharrisichara cf. *P. baytikshanesis*																				x	
Rhabdochara sp.									x												
Stephanochara cf *S. levis*							x			x											
Pollens and Spores: -																					
Aulacoseira sp.														x							
Azolla cretacea			x											x	x						
Aquilapollenites bengalensis														x	x						
Aquilapollenites indicus					x																
Crassitriaperturites gennatus															x						
Cyathidites minor																					x
Dandotiaspora dilata																					x
D. plicata																					x
D. pseudoauriculata																					x
Gabonisporis bacaricumulus					x																
G. vigourouxii			x		x									x	x						
Echitricolporites maristellae															x						
Inapertusporites kedvesii																					x
Lakiapollis ovatus																					x
Lithoparaphysis paproensis																					x
Phragmothyrites eocaenica																					x

Table 9.5. Contd....

Biota	Andhra Pradesh				Gujarat				Karnataka				Madhya Pradesh					Maha-rashtra		Rajas than	Uttar Pradesh
	Asifadad	Rajahmundry	Naskal	Rangapur	Anjar	Bamanbor	Kora	Lakshmipur	Biligi	Gurmatkal	Upparhatti	Yellur	Kisalpuri	Mohgaon-Kalan	Padwar/Ranipur	Mandla	Sagar	Bombay	Nagpur	Mamoni	Lalitpur
Plochmopeltinites cooksoni																					x
Proteacidites reticulatus					x																
Proteacidites cf. *P. miniporatus*					x																
Proxapertites cursus															x						
Proxaperties operculatus															x						
Rutihesperipites trochuensis															x						
Spinizonocolpites baculatus															x						
Spinizonocolpites echinatus														x							x
Stellatopollis araripensis															x						
Todisporites kutchensis																					x
T. major																					x
Toroisporis major															x						
Triangulipollis turonicus															x						
Triporoletes reticulatus															x						
Triporotetradites sp.															x						
Fishes:																					
Selachii: -																					
Myliobatiformes																					
Igdabatis indicus			x										x						x		
Rhombodus sp.	x																				
Rajiformes																					
Raja sudhakari	x																				
Holostei: -																					
Semionotiformes																					
Lepisosteus indicus	x		x	x	x		x						x						x		
Pycnodontiformes																					
Pycnoditidae gen. et sp. indet.	x	x	x										x						x		
Teleostei: -																					
Clupeiformes																					
Clupeidarum sp.				x																	
Harengula sahnii				x																	
Horaclupea intertrappa						x															
Osteoglossiformes																					
Phareodus sp.	x		x	x									x						x		
Osteoglossidarum deccanensis			x	x																	
Osteoglossidarum intertrappus			x	x																	
Notopteridarum nolfi			x	x																	
Salmoniformes																					
Salmoniformorum rectangulus			x	x																	
Siluriformes																					
Ariidae indet.					x			x													
Siluriformes indet.			x										x								
Periciformes																					
Apogon curvatus				x																	
A. spatulatus				x																	
Apogonidarum ovatus				x																	
Chanda ovatus				x																	
Chandidarum sp.								x													
Dapalis bhatiai				x																	
Dapalis sp.			x	x																	
Indiaichthys bamanborensis						x															
Lactariidarum ellipticus				x																	
Palaeopristolepis feddeni						x															
P. chiplonkari						x															
Perca cf. *P. angusta*						x															
Percoideorum ellipticus				x																	
Percoideorum rangapurensis				x																	
Percomorpha indet.						x															
Serranidarum sp.				x				x											x		
Amphibians:																					
Anura: -																					
Anura indet.																			x		
Discoglossidae indet.			x																		
Leptodactylidae indet.			x																		
Ranoidea indet.			x																		
Pelobatidae indet.																			x		
Indobatrachus pusillus																		x			
Reptiles:																					
Chelonia (Turtles): -																					
Chelonia indet.	x		x								x										
Shweboemys (Carteremys) leithii																		x			
Taphrosphys sp.													x								
Squamata (Lizards): -																					
Anguidae indet.			x																		
Lacertilia indet.			x										x						x		
Boidae (Snakes): -																					
Coniophis sp.			x																		
Indophis sahnii			x		x																
Madtsoiinae indet.			x																		
Crocodylia: -																					
Crocodylia indet.	x		x	x									x						x		
Dinosauria:																					
Ornithoid: -																					
Ornithoid eggshell fragments					x																
Subtiliolithus kachchhensis													x								
Sauropoda: -																					
Sauropod eggshell fragments	x				x														x		
Megaloolithus baghensis													x								
Theropoda: -																					
Theropod eggshell fragments					x								x								
Mammalia:																					
Inesctivora: -																					
Deccanolestes hislopi			x	x									x								
Deccanolestes cf. *D. hislopi*			x	x																	
Deccanolestes robustus			x																		
Sahnitherium rangapuri				x																	
Sudamericidae indet.			x																		

10

Cenozoic

INTRODUCTION

The fourth erathem after Archaeozoic, Palaeozoic and Mesozoic is Cenozoic. Though its duration is minimal, areally it covers substantial parts of different continents. Earlier the term Tertiary was coined in a connotation different from what it signifies now. It was the third and the youngest of the major divisions of the earth's crust, being part of Primary, Secondary and Tertiary. This term was used by Giovanni Arduino in 1760. However, later the terms, taking nature of life into consideration, Palaeozoic (early), Mesozoic (middle) and Cainozoic (recent), came into vogue. At present the Cenozoic (Cainozoic) era includes both Tertiary and Quaternary periods. In 1976 the International Commission on Stratigraphy (ICS) divided Cenozoic erathem into Paleogene, Neogene and Quaternary Systems. The descriptions of the stratigraphy are presented under Cenozoic now, in keeping with the present trend and later under Paleogene, Neogene and Quaternary periods. Paleogene Period (ancient born) includes Paleocene, Eocene and Oligocene epochs whereas Neogene Period (new born) includes Miocene and Pliocene epochs (Table 10.1). Paleogene and Neogene are gradually replacing Tertiary as formal period names in scientific literature. Paleogene covers a time span of 42 Ma from 65 Ma to 23 Ma. Neogene covers a time span approximately from 23 Ma to 1.65 Ma (though given as 1.81 Ma by some authors).

In the eighteenth century it was not possible to divide the strata of the Cenozoic on the basis of specific fauna and flora, as most of them, particularly vertebrates, invertebrates, and plants had a wide range within the Cenozoic. In view of this, Gerand-Paul Deshayes considered the percentage of living species of mollusca for the classification of the rocks of the earlier "Tertiary." Since in India substantial amount of literature has been on the "Tertiary," some of the descriptions of stratigraphy and life are confined to this informal period and reproduced as such in some places.

Table 10.1. Cenozoic Linear Time Scale Extracted from International Stratigraphic Chart (2009) (International Commission on Stratigraphy)

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma	GSSP
Phanerozoic	Cenozoic	Quaternary	Holocene		0.0117	⛏
			Pleistocene	Upper	0.126	
				"Ionian"	0.781	
				Calabrian	1.806	⛏
				Gelasian	2.588	⛏
		Neogene	Pliocene	Piacenzian	3.600	⛏
				Zanclean	5.332	⛏
			Miocene	Messinian	7.246	⛏
				Tortonian	11.608	⛏
				Serravallian	13.82	⛏
				Langhian	15.97	
				Burdigalian	20.43	
				Aquitanian	23.03	⛏
		Paleogene	Oligocene	Chattian	28.4 ±0.1	
				Rupelian	33.9 ±0.1	⛏
			Eocene	Priabonian	37.2 ±0.1	
				Bartonian	40.4 ±0.2	
				Lutetian	48.6 ±0.2	
				Ypresian	55.8 ±0.2	⛏
			Paleocene	Thanetian	58.7 ±0.2	⛏
				Selandian	~ 61.1	⛏
				Danian	65.5 ±0.3	⛏
	Mesozoic	Cretaceous	Upper	Maastrichtian	70.6 ±0.6	⛏
				Campanian	83.5 ±0.7	
				Santonian	85.8 ±0.7	
				Coniacian	~ 88.6	
				Turonian	93.6 ±0.8	⛏
				Cenomanian	99.6 ±0.9	⛏
			Lower	Albian	112.0 ±1.0	
				Aptian	125.0 ±1.0	
				Barremian	130.0 ±1.5	
				Hauterivian	~ 133.9	
				Valanginian	140.2 ±3.0	
				Berriasian	145.5 ±4.0	

⛏ refers to Global Boundary Stratotype Section and Point (GSSP)

DISTRIBUTION

A striking feature of the distribution of the Cenozoic (Tertiary + Quaternary) basins in the subcontinent is their peripheral arrangement indicating that the craton had remained an elevated massif without any sedimentation in the central part, in the Cenozoic era. On the other hand orogenic belts and their associated foredeeps demarcated the NW, N and NE borders of the craton, the remaining sides being occupied by pericratonic shelves and deep marine basins. There are no platformal deposits along the Himalayan orogenic belts and along the foredeep of the Himalaya.

During the Neogene period, after Mid-Miocene, the Tethys Sea in the north got obliterated due to tectonic movements. A sea persisted in the remaining areas. Although the degree of mobilization varied in different basins, the tectonic movements reached their culmination during the Quaternary.

In India no single basin provides a complete Tertiary marine succession except for Neogene composite succession of deep marine strata in Andaman-Nicobar basin. Some of the subsurface sections have become important as they provide a relatively more uninterrupted succession, when compared to surface exposures particularly in Assam, Krishna-Godavari, Cauvery and Cambay basins. Most of the lithostratigraphic units recognised, however, are time transgressive. Cenozoic sediments are distributed in the Lesser Himalayan foothill areas of Jammu and Kashmir, Punjab, Himachal Pradesh and Uttaranchal States. Here the Cenozoic rocks commence with the Subathu followed by Dagshai, Kasauli and Siwalik formations in the ascending order.

TECTONICS

The Tertiary rocks in the Himalayan Foredeep are dominated by clastic components and the grain-size has been considered as one of the important parameters to reflect the regional effect. The grain-size of these rocks is basically controlled by factors like (i) uplift in the provenance, (ii) subsidence in the depositional basin and (iii) geomorphic environment. The geological models of the development of the Cenozoic Foredeep of the Himalaya suggest that sedimentation trends besides based on grain size also reflect the main phases and pulsations of Himalayan uplift.

Tectonics has induced a multifaceted cyclicity on Cenozoic sedimentation in the Himalayan Foreland Basin and the Indo-Gangetic Foredeep. The most spectacular cyclic aspect is the mega cycles or energy sequences, which have produced regionally correlatable stratigraphic units, called enseqs (Fig.10.1). It is inferred that the (i) thicker and (ii) thinner sequences in the depocentres

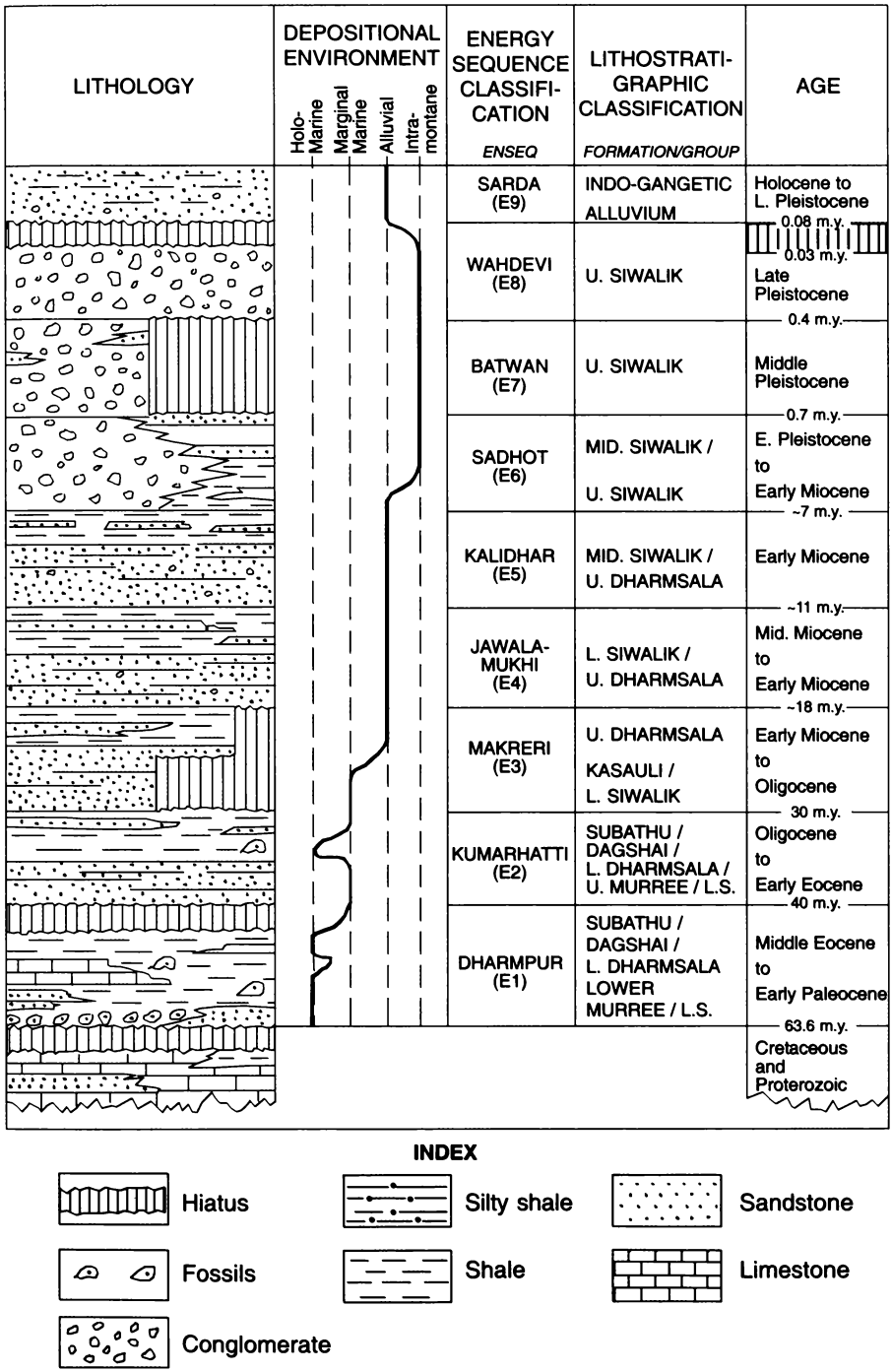


Fig.10.1. Chart showing the Cenozoic succession in Western Sub-Himalaya and Indo-Gangetic foredeep including age, generalised lithology, depositional environment, energy sequence and conventional lithostratigraphy. Note the dichronous status of lithostratigraphy. (modified after Raiverman and Rashid, 1998, p.76).

may reflect respectively (i) the uplift of the provenance and (ii) the relative lower profile (topography). Continental transgressions and regressions leading to expansion and shrinkage of the basinal area of deposition also influence cyclicity. Figure 10.1 shows a suggested generalised energy sequence classification of the Cenozoic succession in Western Sub-Himalaya and the Indo-Gangetic Foredeep. The lithology represents the conglomerates, sandstones, shales and limestones with negligible fossil content. The general applicability of the energy sequence has been, however, debated.

Two most significant geological events in the Cenozoic are noteworthy. These include the continental collision and the phased episodic uplift of the Himalaya and secondly the remarkable fall of sea level in the Indian shelves in the Quaternary and its subsequent rise. The Himalayan orogeny led to the termination of the Tethys. Nine major events were recognised during 65, 60-58, 44, 35, 31, 28-22, 16, 12 and 3 Ma.

Substantial amount of sediment deposited in the distal Bengal Fan can be ascribed to a significant first cycle of uplift and erosion in the collision zone. Moreover the data also indicate that throughout the Neogene, some part of the Himalayan orogen was undergoing rapid erosion (1 to 10 mm/yr), and the erosion must have been less than or equal to uplift, related to sea level.

Cenozoic rocks of the area between Narmada and Tapi (also known as Tapti) rivers have undergone folding, faulting and partial erosion, whereas those of the adjoining area of the Cambay basin to the west lie undisturbed tectonically under the cover of Quaternary deposits. The exposed Tertiary sequences in the Narmada-Tapi region are folded into anticlinal folds, plunging southwest and at times northeast as well, and are invariably faulted along their southeast limbs. These faults are of reverse type with hade to the northwest. The deformation was caused due to differential movements along the basement fault (Narmada-Son Fault) related to the northward movement of the Indian Plate.

MAGMATIC ACTIVITY

Tectonic movements under thick rock piles in the Himadri (Great Himalaya) resulted in the melting of some of the metamorphic rocks giving rise to granites in the form of large batholiths that discordantly cut through rock successions as smaller bodies like laccoliths, sills, dykes and veins. Some migmatites were formed in the process. The massifs of Badrinath and Kedarnath in Garhwal are made up of 1.5 to 2.0 km thick slab-like rock bodies called laccoliths (of light-coloured granite) formed nearly 20-22 Ma ago. Besides the above, anatectic granite that formed near the top of the Himadri complex were of an age between 25 to 15 Ma, the peak activity dated about 21±0.5 Ma ago of Early Miocene.

CLIMATE

An integrated analysis of time-space relationship of certain specific lithofacies in the Cenozoic basins of the Indian subcontinent shows that palaeoclimate has left an unmistakable imprint in shaping the lithofacies. Between Paleocene and Holocene there were several global cycles of cold and warm phases. Under favourable geomorphic environment, coal and lignite have formed only during those intervals of time when climate was changing from cold to warm i.e. during Late Paleocene, Early Eocene, Late Oligocene-Early Miocene, and Late Miocene-Early Pliocene intervals. Limestone deposition took place in warm phases of Paleocene, Middle Eocene, Oligocene and Early Miocene. The restricted occurrence of evaporite facies during Paleogene period, in the basins situated on the western side of the subcontinent, points to arid conditions. This is analogous to the present day climate zones of the subcontinent under monsoonal influence.

CORRELATION

Regional correlation of Himalayan Cenozoic rocks has remained problematic for the following reasons:

(i) Restricted occurrence of fossils and marker beds,
(ii) limitations of mineralogical composition as a correlation tool and
(iii) lateral variations in lithofacies.

A heavy mineral clock (HM) based on heavy mineral distribution pattern in time has been extensively used for correlating Cenozoic rocks in the Indo-Gangetic basin – 3.5 to 4 km thick and also in the subsurface in Upper Assam – 2 to 3 km thick.

A very detailed biochronostratigraphic framework for the Cenozoic sequences of India has been proposed by the geologists of ONGC mainly based on offshore data (Fig. 12.2). Many hiatuses have been identified. These data provide criteria to demarcate the various stage boundaries in Indian sedimentary basins. Indian stages are named after the holostratotypes and a standard Indian chronostratigraphic succession has recently been established (Raju et al., 1999). A limiting factor, however, in this study is that some of the stages have been derived from subsurface data.

FAUNA AND FLORA

Fauna

During the Tertiary mollusca, echinoid (Plate 10.3 – 1 to 12), corals,

decapoda crustaceans, bryozoans, annelids and barnacles occur in decreasing order of abundance. Foraminifera are one of the most extensively studied groups of microfossils, due to their wide application in several fields of geology (Plates 10.1, 10.2 and 10.3 – 13 to 24). Nannoplanktons – the tiniest marine calcareous microfossils, known for their great rapid evolutionary changes, have been used with great success in biozonation of Cenozoic, especially the species of *Discoaster* in Paleogene. A few invertebrate species have also been of great value as time marker, such as bivalvia *Ostrea angulata* and *O. latimarginata* in Lower Miocene.

The term 'larger foraminifera' is used for those benthonic species having complex internal morphology and minimum volume of 3 mm^3. They are major sediment constituents in shallow water carbonates of Permo-Carboniferous, Cretaceous, and Cenozoic. They are confined to the euphotic zone of the marine shelves. The modern taxa are largely confined to <60 m of water depth, although in the Gulf of Aquaba, northeastern Egypt, the lower limit of larger foraminifera is at 130 m. Temperature is another important factor because temperatures in excess of 20-22°C are probably necessary for reproduction. The nature of the substratum, salinity and energy conditions are some of the other factors long since recognised as controlling the distribution of larger foraminifera. Middle Eocene marks the period of highest diversity and highest origination rate. Per capita origination rate was, however, the highest in Paleocene. During the Late Eocene there was 60% generic reduction. It shows the highest rate of extinction, a fairly high rate of origination and the maximum turnover rate. The extinction of Cretaceous planktonic foraminifera is ascribed to predation and adverse climatic conditions lasting for about 50,000 years.

Regression of the sea, low stability and sea level cycles, and sharp climatic deterioration together seem to have determined the extinction maxima of the Paleogene larger foraminifera in Late Eocene.

There were quite a few reefal bodies (algal bioherms) developed during Cenozoic, particularly in southeast India and Kutch (Gujarat). The rocks comprising the reefs are hard, compact to vuggular and grey, pink to cream coloured algal biolithites of biosparite to biomicrite type, which are generally devoid of terrigenous sediments. The coralline algae like *Lithothamnion*, *Amphizoa*, *Lithophyllum*, *Mesophyllum*, *Halimeda* etc. are the primary builders of these bioherms.

Ostracodes occur practically in all aquatic environments ranging from fresh water, marginal marine to shelf and deep marine waters. Certain ostracode species have short vertical stratigraphic range and many evolve rapidly. All these factors combine to make the ostracodes potentially a very useful group of microfossils for time stratigraphy and palaeoenvironmental studies. Ostracoda bioevents have been recognised on the basis of First Appearance

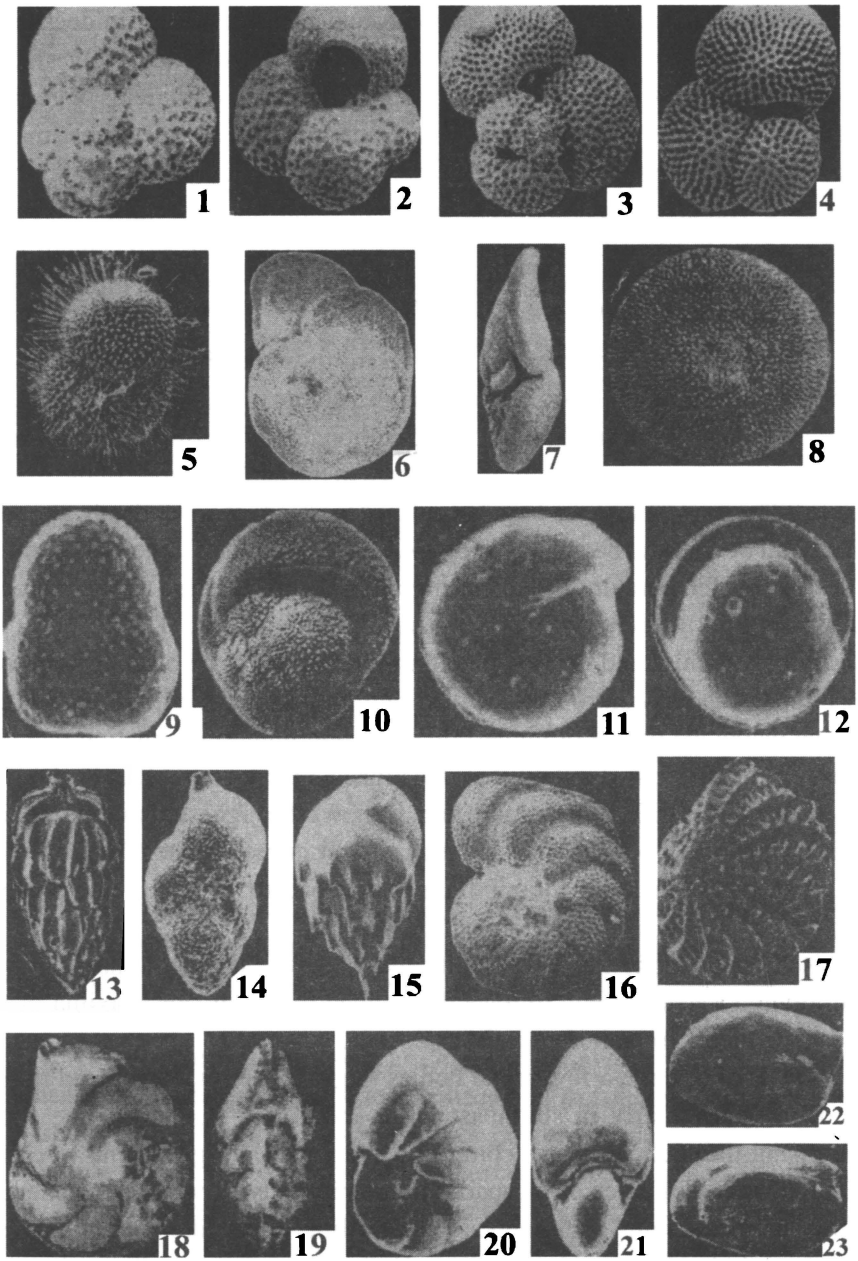


Plate 10.1. 1-2 - *Globigerina rubescens* (Upper Pliocene); **3-4** - *Globigerinoides trilobus trilobus* (Lower Miocene); **5** - *Globigerinoides ruber* (Pliocene-Recent); **6-7** - *Globorotalia tumida tumida* (Pliocene-Recent); **8** - *Orbulina universa* (Middle Miocene-Recent); **9** - *Sphaeroideinellopsis seminulina* (Middle Miocene-Pliocene); **10** - *Pulleniatina obliquiloculata* (Pleistocene-Recent); **11-12** - *Pullenia bulloides* (Oligocene-Recent); **13** - *Uvigerina peregrina* (Miocene-Recent); **14** - *Uvigerina proboscidea* (Miocene-Recent); **15** - *Bulimina striata* (Pliocene-Recent); **16** - *Planulina wuellerstorfi* (Upper Pliocene-Recent); **17** - *Elphidium crispum* (Miocene-Recent); **18-19** - *Lenticulina convergens* (Oligocene-Miocene); **20-21** - *Nonion labrodorim* (Pliocene-Pleistocene); **22** - *Triloculina inflata* (long ranging); **23** - *Quinqueloculina seminulum* (long ranging) (Courtesy: A Govindan and D.S.N. Raju).

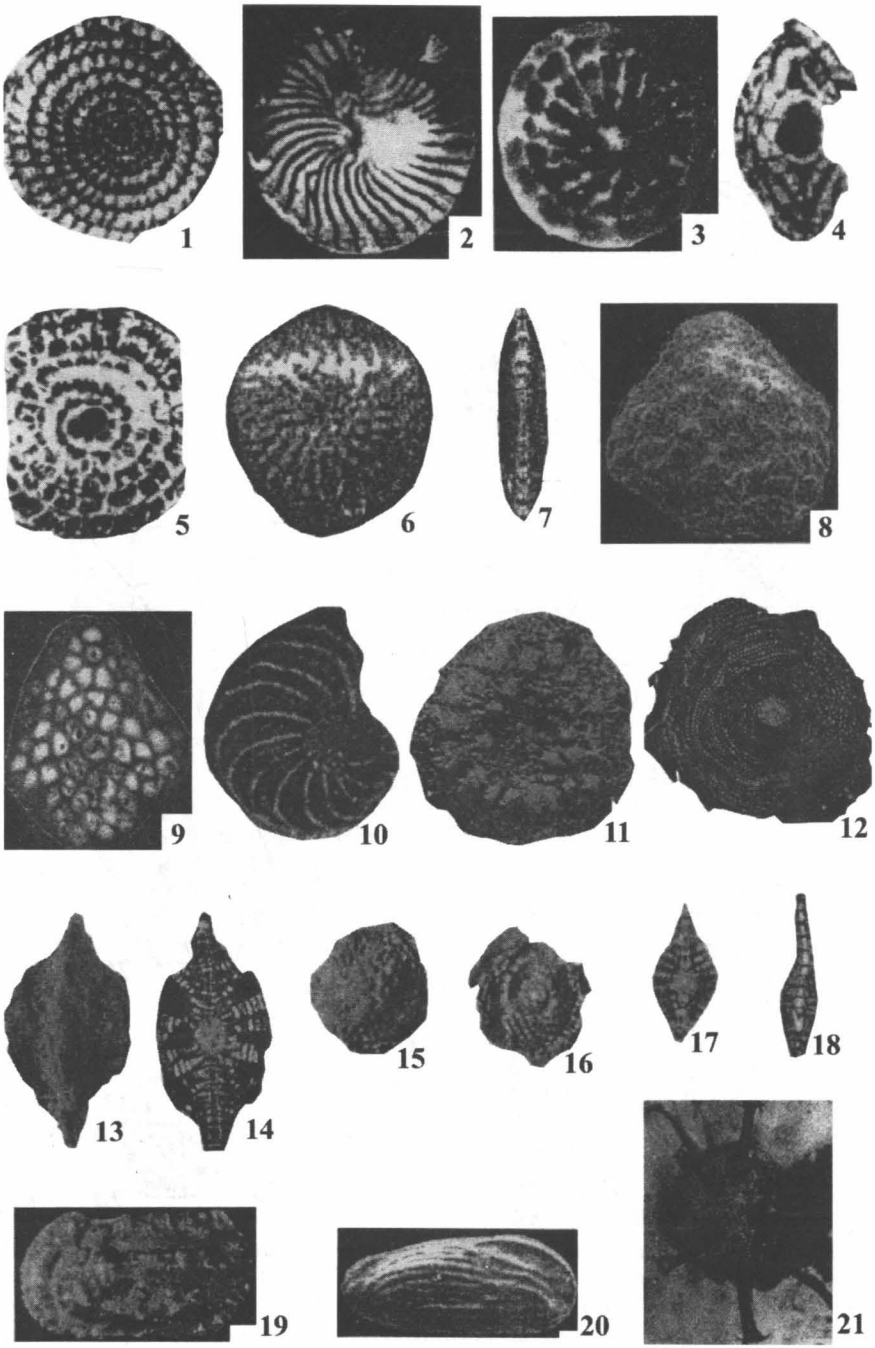


Plate 10.2. 1-2 - *Nummulites striatus* (Upper Eocene); **3-5** - *Nummulites prever* (Upper Eocene); **6-7** - *Assilina laminose* (Eocene); **8-9** - *Miogypsina globulina* (Lower-Middle Miocene); **10** - *Operculina complanata* (Late Paleocene-Miocene); **11-14** - *Lepidocyclina angulosa* (Middle Miocene); **15-17** - *Spiroclypeus margaritatus* (Miocene); **18** - *Heterostegina borneensis* (Lower Oligocene-Lower Miocene); **19** - *Actinocythereis tumefacentis* (Lower Miocene); **20** - *Costa buntonia hartmani* (Paleocene); **21** - *Homotrybilum tenuispinosum* (Eocene). (Courtesy: A. Govindan)

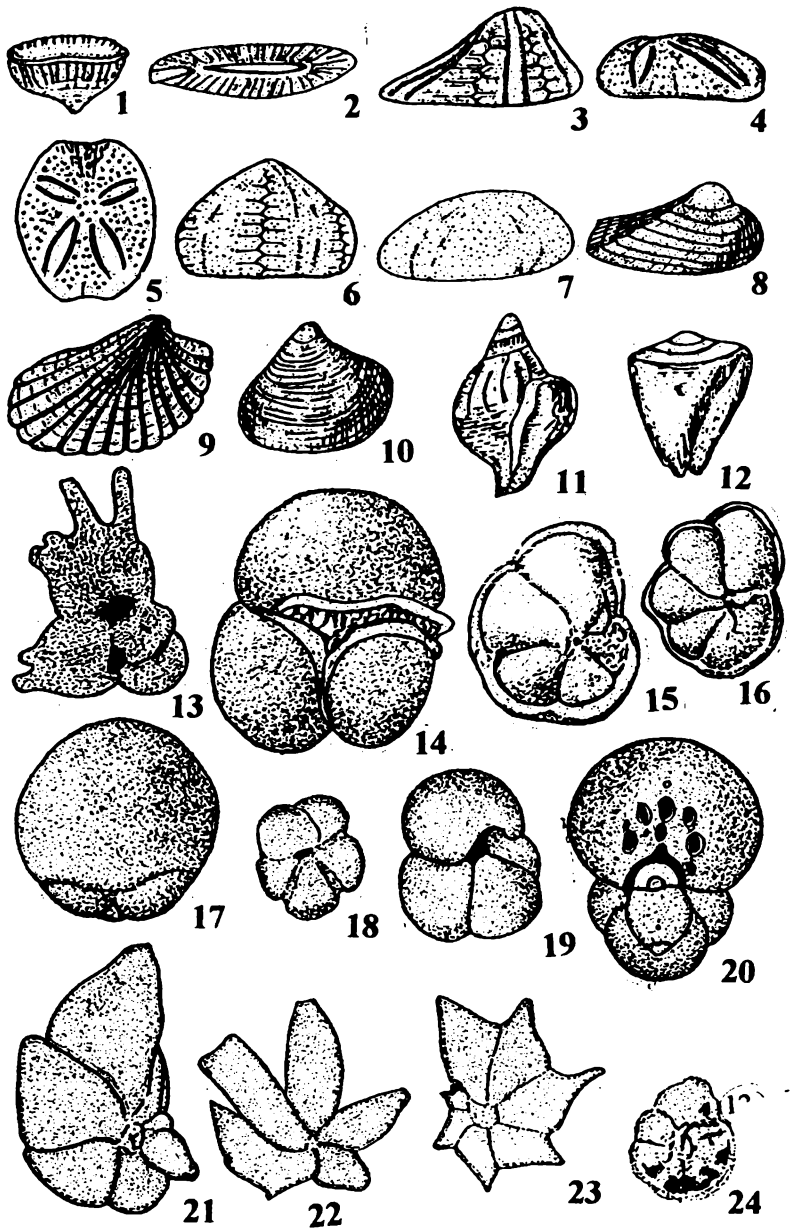


Plate 10.3. 1-2 - *Trochosmilia medlicotti*; **3** - *Conoclypeus sindensis;* **4-5** - *Macropneustes speclosus;* **6** - *Conoclypeus alveolatus*; **7** - *Echinolampas desori*; **8** - *Corbula socialis*; **9** - *Arca burnesi*; **10** - *Cyrena crawfordi*; **11** - *Cacellaria martiniana*; **12** - *Conus literatus* (with different time ranges in Cenozoic); **13** - *Globigerinoides trilobus fistulosis* (Pliocene); **14** - *Sphaeroidirulla dehiscenus* (Pliocene-Recent); **15** - *Globorotalia tumida tumida* (Pliocene-Recent); **16** - *Globorotalia fohsi lobata* (Middle Miocene); **17** - *Praeorbulina glomerosa glomerosa* (Miocene); **18** - *Globorotalia kugleri* (Lower Miocene); **19** - *Globigerina ampliapertura* (Upper Eocene-Lower Oligocene); **20** - *Cribrohantkenina inflata* (Upper Eocene); **21** - *Hantkenina dumblet* (Lower part of Middle Eocene); **22** - *Hantkenina nuttale*; **23** - *Planorotalites palmerae* (Upper part of Lower Eocene); **24** - *Morozovella velascoensis* (Upper Paleocene) (Courtesy: U.B. Mallikarjuna and D.S.N. Raju).

Datum (FAD) and Last Appearance Datum (LAD). Ostracod bioevents are correlatable at inter- and intra-basinal levels along the West Coast basins of India.

An analysis of affinities of Late Eocene – Oligocene – Early Miocene mammalian faunas of the Indian subcontinent reveals markedly different pictures for the smaller and larger mammals. While the former are endemic, the latter are mixed with Asian, European, North American as well as African elements.

Flora

The available palynofloral data for the Paleocene-Eocene exhibit the characteristics of tropical vegetation particularly reflecting semi-evergreen type to mixed coastal type depending upon the prevailing environmental conditions. However, the composition of the Late Eocene to Early Miocene palynofossils depicts a gradual shift towards colder climate, which marks the appearance of moist deciduous forests. The Middle Miocene palynofloras in Western Himalaya generally conform to subtropical moist deciduous vegetation types. The Middle Miocene orogeny of the Himalaya elevated the range sufficiently high, which accelerated the migration of plant taxa from the Mediterranean, Sino-Japanese and Malayan regions. Further rise of the Himalaya during the Late Miocene-Early Pliocene resulted in colder climate, lesser precipitation and increased aridity. These conditions proved harsh for moisture-loving plants viz. *Dipterocarpus* and others. They either perished or moved away to Peninsular Indian areas in the south where equitable climate proved conducive for their growth. Cold loving plants *Pinus*, *Tsuga* etc. established themselves well on the elevated slopes of the Himalaya during this period.

CLASSIFICATION

In his classical work of 1876-1879, W.T. Blanford introduced a new classification of the Tertiary rocks of Sind. For nine decades between 1879 and 1965, the nomenclature of Nari, Gaj and Manchar Series, which were first christened for exposed sections in Sind and Baluchistan (in Pakistan since 1949) was widely used in the classification and correlation of the Oligocene-Miocene sediments of the Indian subcontinent. Subsequently independent nomenclatures have been developed in the different regions of India, using local names.

Detailed study of mega- and microfossils, particularly those of Kutch, by ONGC and other agencies, led to a chronostratigraphic classification of Tertiary. This nomenclature is now being used for correlation of Tertiary rocks of the Western Offshore basins in India. This scheme is mainly applied to the pericratonic platformal deposits.

STRATIGRAPHY

Tertiary stratigraphy of some of the regions is briefly presented below:

Gujarat

The Tertiary rocks in Gujarat occur in all the three geographical sub-divisions of Gujarat namely the Mainland, Saurashtra and Kutch. Exploratory drilling in parts of the Mainland has brought to light subsurface information as well. Table 10.2 gives an integrated correlation chart with data from Merh (1995). The lithology and fossil content of these formations/series are shown elsewhere. The Tertiary marine sequence of Kutch is considered to represent sedimentary deposits of the stable shelf of a pericratonic rift basin.

Rajasthan

The Cenozoic rocks of Rajasthan comprise marine to continental sedimentary sequences that were deposited over the Mesozoic sediments in Jaisalmer, Barmer and Bikaner-Nagaur basins. Figure 10.2 presents the geological and tectonic map of the Jaisalmer basin and the adjoining areas. The distribution of Cenozoic formations in different basins of Western Rajasthan is given in Fig.8.5. The lithology and fossil content of the formations are given in other sections of this chapter.

Jammu and Kashmir

Tertiary rocks are well exposed practically all along the foothills of Himalaya. Siwalik strata form a part of these:

Jammu	Siwalik	Upper 1800 m Middle 1800 m Lower 1500 m	
	Murree	Upper 900 m Lower 1500 m Basal - Fatehjang zone of fossiliferous conglomerates	
	Chharat Stage	Nummulitic shales, limestones and marls	Middle Eocene
	Hill Limestones	Massive Nummulitic Limestones with coaly layers	Lower Eocene
	(after Krishnan, 1982, p.428)		
Kashmir	Molasse		Oligo-Miocene Eocene

Table 10.2. Correlation of Cenozoic formations in Gujarat (simplified from tables on pages, 96, 119, 125 and 150 in Merh, 1995 and modified)

			MAIN LAND		Saurashtra	Kutch
			Subsurface	Surface		
Quaternary		Holocene	Gujarat Alluvium	Narmada Alluvium	Soils, Alluvium Gravel and Sand Chaya Fm. Miliolite	Alluvium Rann Miliolite
		Pleistocene	Jambusar Fm.	Absent	Dwarka Fm. of Western Saurashtra Piram Beds of Southern Saurashtra	Sandhan Fm. Chasra Fm. Khari Nadi Fm.
Tertiary	NEOGENE	Pliocene	Broach Fm.	Absent		
			Jagadia Fm.	Jagadia Fm.		
		Miocene	Kand Fm.	Kand Fm.	Kuda Sandstone Bhumbli Congl.	Maniyara Fort Fm.
			Babuguru Fm.	Babuguru Fm.		
	PALEOGENE	Oligocene	Tarakeshwar Fm.	Absent		
		Eocene U	Dhadar Fm.	*Pellatispira* Beds	Ratnapur Clay	
		Eocene M	Ankaleswar Fm.	Dinod Fm.		Fulra Fm. Harudi Fm.
		Eocene L	Cambay Shale			Matanumadh Fm.
		Paleocene(?)	Vagadkol Fm.	Vagadkol Fm.		
Cretaceous			Deccan Traps	Deccan Traps	Laterite Deccan Traps	Deccan Traps

Himachal Pradesh

It was Medlicott who proposed the following classification of the rocks of the Siwalik Range.

- Siwalik Series
  - Upper
  - Middle
  - Lower (Nahan)
- Sirmur Series
  - Upper (Kasauli)
  - Middle (Dagshai)
  - Lower (Subathu)

(Dharamsala (after ONGC))

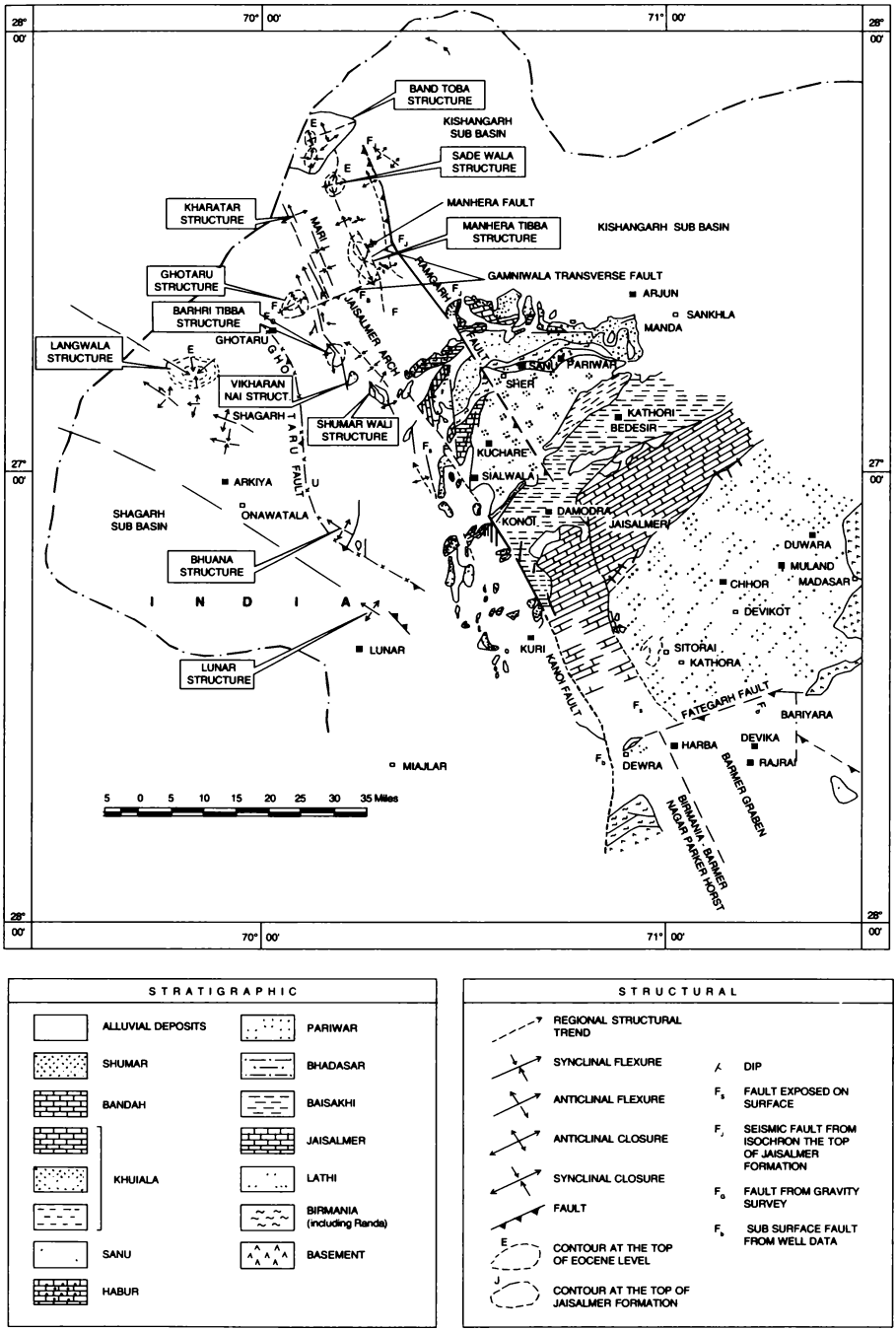


Fig.10.2. Geological and tectonic map of the Jaisalmer basin and adjoining areas, western Rajasthan (after Das Gupta, 1975) (source: Sinha-Roy et al. 1998, p.220)

With the exception of Subathu sediments, the entire overlying Cenozoic sequence is of fresh to brackish water origin. Mega-fauna in the post-Subathu sequence is sporadic in occurrence and is of no help in stratigraphic subdivision and correlation. Palynology has therefore been considered for reconstructing biostratigraphy.

Trace (=ichno) fossils have been helpful in inferring the palaeoenvironments of Tertiary rocks in particular. Primary sedimentary structures and lithological associations in Subathu-Dagshai-Kasauli succession (Eocene-Miocene) of Simla hills indicate almost continuous deposition without any significant time-break or unconformity, and it is possible to characterise the three formations on the basis of distinct trace fossil assemblages. The Subathu sediments show characteristic features of an open sea deposit (shelf mud, tidal flats and sandbars), deposited partly in hypersaline and reducing conditions. Trace fossils of the Subathu Formation are a few stout horizontal *Thalassinoides*, *Chondrites* and *Tiggilites*. The open tidal sea of Subathu times changed to an estuarine complex with extensive mud flats under marine influence in which Dagshai sediments are deposited. The Dagshai Formation shows various types of *Thalassinoides* burrows, *Chondrites* and minute feeding burrows in abundance. The estuarine complex of Dagshai period changed to an alluvial plain with subtly shifting braided streams during the Kasauli period, which is characterised by the horizontal burrows of various insects, e.g., beetle and cricket.

Punjab and Ganga Basin

The demarcation of palyno- and ecozones in the Siwalik, Murree, Dharamsala and Subathu Formations of rocks of Himalayan foothills have been helpful in the recognition of three marine incursions in the Tertiary sequences during the Paleocene/Early Eocene, Late Eocene and Middle Miocene epochs. The Murree/Dharamsala and the Subathu Groups have been assigned Lower Eocene to Middle Miocene age on the basis of faunal content, while the Paleocene age to the base of the Subathu Group has remained a point of contention. However, tentatively, the formations here are assigned the ages given below:

Formation		Age
Siwalik	Upper	Pliocene
	Middle	Upper Miocene
	Lower	Middle Miocene
Murree/Dharamsala		Oligocene-Miocene
Subathu		Lower – Middle Eocene (Paleocene?)
Crystalline Basement Complex - Archaean		

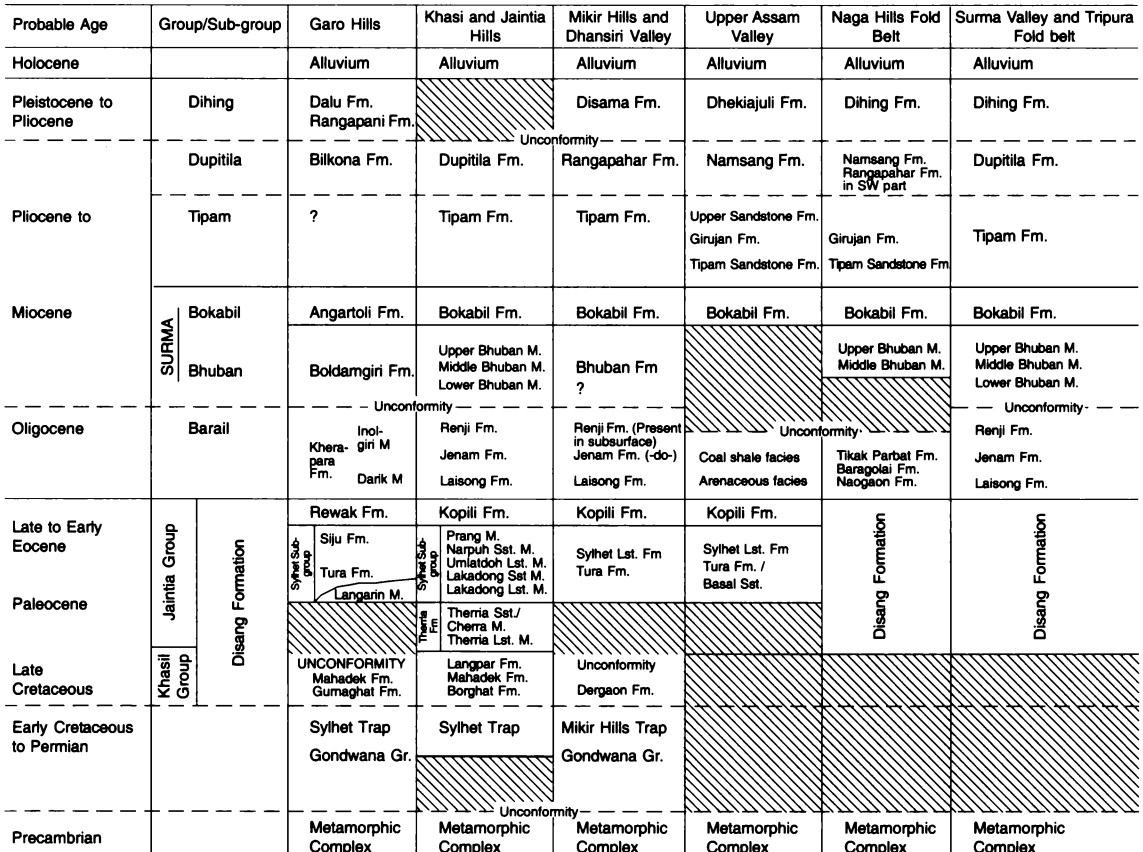


Fig.10.3. Generalised stratigraphic sucession in Assam-Arakan Basin (source: Roy and Asthana, 1989)

The Tertiary sedimentation in the Ganga basin is similar to that of the Sub-Himalayan Punjab basin, as both the basins were affected by Himalayan orogeny during the Tertiary. The Subathu sediments are not encountered in well sections of the Indo-Gangetic Plain. The Vindhyan rocks are directly overlain by Neogene Siwalik sequences.

Northeastern India

The collision between India and Myanmar (Burma) from northeast towards southwest in Northeastern India formed three important zones of Tertiary sedimentation. These zones are:

(i) Shelf zone (around Shillong-Mikir hills plateau edge, as well as the submerged basement spur)
(ii) Naga schuppen zone – a deep marginal sedimentary basin
(iii) Kohima synclinorium and the receding Indo-Myanmar gulf, now occupied by the Surma valley-Chittagong hills belt and the residual basins in Sylhet and Bengal

In all these areas, the Late Eocene and younger sediments have very few diagnostic macrofossils. Hence the initial rock nomenclature, correlation and classification were based on lithology and heavy mineral studies. Micro-paleontology and palynology, which followed later, proved to be highly rewarding. The generalised stratigraphic succession arrived at in this region based on studies by various organisations is presented as Fig10.3.

Andaman-Nicobar Islands

The Cenozoic succession of Andaman and Nicobar group of islands is given here as Table 10.3. All the rocks of this succession are of marine origin and the relative ages determined are based on the study of micro-fossils.

Kerala/Maharashtra

Tertiary sequences in Kerala and near Ratnagiri in Maharashtra are represented by rocks of Neogene age. In Kerala, there occurs a linear belt east of Cannanore (Kannur) and from Cochin (Kochi) to Thiruvananthapuram (Trivandrum). The Tertiary rocks in the coastal plains of Kerala have yielded Early Tertiary planktonic foraminifera as well as palynofossils of Early Eocene age in a 600 m borehole. Occurrence of ferruginous sandstone with arkose and clay below the Tertiary sequence is also reported.

Table 10.3. Classification of Cenozoic succession of Andaman-Nicobar Islands (based on Srinivasan and Azmi, 1976 and Roy, 1983) (source: Ravindra Kumar, 1996, p.219)

Group	Formation	Lithology	Age
	Shell limestone, beach sand	Coral rag and sand	Sub-recent to Recent
	– – – – – – unconformity – – – – – –		
	Neil West Coast Formation	Bio-calcarenite	Late Pliocene to Pleistocene
	Guitar Formation	Calcareous mudstone	Early to Late Pliocene
	Sawai Bay Formation	Calcareous mudstone	Late Miocene to Early Pliocene
Archipelago Group	Long Formation	Calcareous siltstone and silty mudstone	Middle to Late Miocene
	Inglis Formation	Calcareous chalk	Early Miocene
	Strait Formation (Round Formation)	Shell sandstone, limestone and conglomerates	Early to Middle Miocene
	– – – – – – unconformity – – – – – –		
	Port Blair Formation	Conglomerate, grit and greywacke	Middle Eocene to Oligocene
Upper Cretaceous Palaeogene Group	Baratang Formation	Shale-greywacke	Late Cretaceous to Eocene
	Port-Meadow Formation	Radiolarian chert, quartzites	Late Cretaceous

PALEOGENE

INTRODUCTION

Paleocene with typical marine fauna is developed in India all along the West Indian Shelf between Rajasthan and offshore Kerala as also in the East Indian Shelf extending northwards into the subsurface of West Bengal and outcrops in southern Shillong front. Though ill-developed, marine Paleocene beds are present in the Himalayan belt. The Paleocene epoch of India, spanning nearly 10.5 Ma is widely represented by marine, nonmarine and effusive sediments. The last are often associated with lava flows without significant thickness as inter-trappean beds to constitute the Deccan Trap. In the northern part of the subcontinent, nonmarine fluvial sedimentation occurred from Upper Eocene to Holocene.

The coal deposits of northeast India occur in the States of Meghalaya, Assam, Arunachal Pradesh and Nagaland, confined to the Eocene and Oligocene formations. These coal deposits have formed in two distinct tectono-sedimentary

settings. The coal occurrences of Garo and Khasi hills of Meghalaya represent the development of coal facies over platform areas under stable shelf conditions, whereas the coal deposits of Upper Assam (Dilli-Jeypore and Makum coalfields), Arunachal Pradesh (Namchik-Namphuk coalfield) and Nagaland (Borjan coalfield) have probably originated in foreland basins. The coal deposits of the foredeeps occur in the Tikak Parbat Formation of Barail Group. The coal seams of Garo and Khasi hills, Meghalaya occur in the Lakadong Sandstone Formation of Jaintia Group and are sandwiched between two limestone formations – the underlying Lakadong Limestone and the overlying Umlatdoh Limestone.

FAUNA AND FLORA

Reef building activity, which was dominant in the Paleocene progressively decreased toward the end of the Paleogene. During the early Paleogene, the coal formation was confined to the eastern borders of the Sindhu Sea (now the Rajasthan region). However, towards the close of the Paleogene, it shifted eastwards. Eocene carbonates are well developed in the East and West coast basins of India, Shillong shelf, Assam-Arakan basin and Himalayan region. These carbonates are rich in larger foraminifera and are characterised by *Alveolina-Assilina-Nummulites-Discocyclina-Pellatispira* suite. Recently (Mathur and Juyal, 2000) a comprehensive monograph has been published on the invertebrate fossils from the uppermost Cretaceous –Lower Paleogene sediments represented by the Kakara-Subathu succession of the Himalayan foothills. The study recognised several faunal communities in the above succession and led to interpretation of palaeoecology and palaeobiogeography during the latest Cretaceous to early Paleogene times. Throughout the Lesser Himalayan belt stretching from Jammu to Arunachal Pradesh, rocks of Early Eocene (Ypresian) age of Subathu Formation are mainly backed by larger foraminiferal and palynofossil data. There is also a report of foraminifer rich facies in Koshalia *nala* section (almost along NH 22 i.e. Kalka-Shimla Road) of Lesser Himalayan belt.

STRATIGRAPHY

Gujarat

The Paleocene rocks in Mainland Gujarat are represented by Vagadkhol Formation. The formation (Table 10.2) occurs along the eastern margin of the Tertiary rocks with the Deccan Trap and forms a number of discreet outcrops forming anticlinal flexures. The constituent rocks are conglomerates and variegated clays, a material mostly derived from the weathering of the basalt. Lithological characteristics indicate fluvial to marginal marine oxidizing

Table 10.4. Tertiary stratigraphy of Kutch (modified from Sastri, 1988, p.411)

Age		Biswas (1971, 1973)		Mohan & Soodan (1967, 1970); Mohan & Bhatt (1968); Raju (1971); Raju & Biswas (1973)	
		Rock units	Time - Stratigraphic	Biostratigraphic Zones	Important Foraminifera
Pliocene		Sandhan Fm.	Kankawati Series	Miliolid Assemblage Zone	*Ammonia beccardi*, *Quinqueloculina* sp. *Triloculina* sp.
Miocene		Charra Fm.	Khari Series / Unconformity / Vinjhan Stage	*Miogypsina excentrica* Zone	*Lepidocyclina sumatraensis*, *Archaias angulatus*, *Sorites*, *Austrotrillina howchini*, *Gypsina globulus*, *Ammonia beccarii*, *Uvigerina*, *Discorbis*
				M. *droogeri* Zone	
		Khari Nadi Fm.		*M. globulina* - *M. thecidaeformis* Zone	
Oligocene		Maniyara Fort Fm.	Bermoti Series / Aida Stage	*M. tani* Zone	*Rotalia* sp., Miliolids, Cibicides
				Poorly fossiliferous zone	
			Waior Stage	*M. complanata* - *Miogypsinoides formosensis* Zone	*Spiroclypous ranjanae*, *Pararotalia mexicana*, *Operculina* sp.
			Ramania Stage	*M. fichteli* / *Lepidocyclina dilarata* *M. fichteli* Zone	*Operculinoides* sp., *Operculina* sp., *Heterostegina* sp.
Eocene	Late				
	Middle	Fulra Limestone Fm.	Berwali Series / Babia Stage	*Truncorotaloides rohri* Zone	*Guembelitria columbiana*, *Turborotalia centralis*, *Gypsina globulus*
		Harudi Fm.		*Orbulinoides bechmanni* Zone	*Globorotalia lehneri*, *Truncorotaloides rohri*
				Globigerina kugleri - *G. frontosa* Assemblage Zone	*Pseudohastigerina micra*, *Catapsydrax dissimilis*
				Hantkenina aragonensis Zone	*Chiloguembelina martini*, *Turborotalia centralis*, *Globigerina yeguaensis*, *Truncorotaloides rohri*
	Early		Unconformity / Kakdi Stage	Poorly fossiliferous Zone	
		Nareda Fm.		*Globorotalia rex* Zone	*Globorotalia imitata*, *G. tribulosa*, *Globigerina aqueinsis*, *Globanomalina wilcoxensis*
Paleocene		Matanomadh Fm.	Madh Series	Poorly fossiliferous Zone	

conditions. The formation is unfossiliferous and overlies the Deccan Trap unconformably.

The equivalent of Vagadkhol Formation of Mainland has been termed as Madh Series in Kutch (Table 10.2). It consists of tuffs, volcanic ash, tuffaceous shale and sandstone and bentonitic clay, and overlies the basalt. These have yielded dicot leaf impressions, spores and pollens. On the basis of plant fossils, it has been assigned Paleocene to Lower Eocene age. Lignite seams are associated with Lower Carbonaceous Shale Member of the Paleocene-Eocene Panandro Formation. The lignite deposits are spread over an area of about 45 sq.km in Panandro, Umarsar, Akrimoto, Matanomadh, Lefri Jhubrai fields of Kutch district.

Overlying unconformably the Vagadkhol Formation in Mainland is the Dinod Formation of Eocene, which comprises a fossiliferous limestone. The limestone is compact and massive, yellow in colour, and at places it is coquinoidal, replete with molluscan shell fragments and has several species of larger foraminifera Discocyclina and Nummulites. A Middle Eocene age has been assigned to this formation. Upper Eocene Tapti Series in Surat- Broach area is represented by limestone containing foraminifera Pellatispira madaraszi and Nummulites fabianii. Outcrops are seen near Dinod, Bhilod and in Tapti River section.

In Kutch the Eocene is represented by the Berwali Series. This is divisible into two stages – the Kakdi and the Babia. The former has black shales with bands of lignite, bitumen and pyritous shale. The latter consists of dense fossiliferous fragmental limestone and numerous distinct fossil zones. This series is considered to represent Lower and Middle Eocene.

In the Mainland Gujarat, Oligocene rocks are absent, though they are met with in subsurface as Tarakeshwar Formation of about 175 m.

In Kutch (in Lakhpat I Well) the Oligocene is represented by Ramania and Wair Stages. The former consists of greenish grey marl and argillaceous limestone with a basal boulder clayey marl bed and the latter is made up of a basal oolitic band followed by fossiliferous marl. An Oligocene age has been assigned to the Ramania Stage that shows abundant development of reticulate Nummulites in the lower part, and with the first appearance of *Lepidocyclina* (*Eulepidina*) along with reticulate *Nummulites* in the upper part suggesting Lattorfian (Lower Oligocene) and Stampian (Upper Oligocene) ages respectively. The overlying Waior Stage has been considered as Chattian (Upper Oligocene) on the basis of *Spiroclypeus-Miogypsinoides complanata* assemblage. The foraminifera are supposed to indicate lagoonal and subtidal conditions. The biostratigraphic zones and important foraminifera in the Tertiary stratigraphy of Kutch are presented in Table 10.4. Ostracodes are seen in rocks of Paleocene – Eocene to Oligocene from Lakhpat in NNW to Goyela in the SSE, in the western part of Kutch Mainland.

Rajasthan

There are three basins namely, Jaisalmer, Barmer and Bikaner-Nagaur in which Paleogene rocks are present (Fig.8.5).

In Jaisalmer basin the Paleocene is represented by Sanu Formation. A sequence of sandstone and shale unconformably overlies the Habur Limestone and Pariwar Sandstone, both of which belong to Lower Cretaceous. The sequence commences with glauconitic clay that passes upward into a coarse-grained gritty sandstone. A rich crop of sporomorph, fish teeth and gastropod shells is reported from the subsurface. The age is considered to be Paleocene. The Khuiala Formation disconformably overlies the Sanu Formation. Limestone and shale constitute the lithology of the formation. The formation is rich in fossils of Lower Eocene larger foraminifera *Assilina daviesi*, *A. granulosa*. The Bandah Formation conformably overlies the Khuiala Formation and is characterized by the presence of Middle Eocene larger foraminifera *Discocyclina sella*, *D.dispensa*, *D. sowerbyi*, *Nummulites maculatus*, *Alveolina elliptica* etc. The geological and tectonic map showing the distribution of the Tertiary formations in Jaisalmer basin is given in Fig.10.2.

In Barmer basin it is represented by Akli Formation. It comprises of ferruginous sandstones, bentonite, bentonitic clay, siliceous earth, ferruginous shale and phosphatic sandstone. It overlies Fatehgarh Formation. In the lower part, the sequence is carbonaceous, containing gypsum and pyrite. Rich assemblage of foraminifera, echinoids, mollusca, coral, ostracoda, fish and leaf impressions is reported from the Akli Formation. This is followed by Mathaji ka Dungar Formation. This commences with a conglomerate, which passes upward into sandstone. Casts of lamellibranchs and gastropods and leaf impressions are commonly found. The age is Paleocene to Lower Eocene. Overlying this formation is the Kapurdi Formation comprising fuller's earth with ferruginous and gypsiferous concretions and bioclastic limestone. The fossil assemblage includes foraminifera, nannoplankton, ostracodes, echinoids and bivalves of Lower Eocene age.

Palana Formation of Paleocene age and Marh Formation of Upper Palaeocene to Lower Eocene age are met with in the Bikaner-Nagaur basin, the latter comprise grit and sandstone. Jogira Formation, with alternation of limestone, marl and fuller's earth, conformably overlies the Marh Formation and is of Lower to Middle Eocene age.

Jammu and Kashmir

Paleogene formations (in many places part of Siwalik succession) occur all along the Lesser Himalayan belt, right from Sindh-Salt Range in Pakistan to Myanmar (Burma) (Table 10.5). Paleogene rocks are met with in Jammu, Kashmir and Kargil parts of the State.

Jammu: The Eocene rocks of Jammu region form a 3 to 5 km wide continuous belt, which along with the underlying Permo-Carboniferous rocks, form the autochthonous belt of Wadia, sandwiched between the Murree and Panjal Thrusts. The belt has been traced from Uri towards Budil-Ramban area, beyond which it extends towards Ravi Valley, but wide gaps break up the continuity of the belt. The lower part consists of thin bedded, pale grey, cherty limestone with a few fossils of *Nummulites* and gastropods. They attain a thickness of about 100 to 150 m. The basal part consists of pyritous, coaly and ferruginous shales with thin carbonaceous beds. There are also a series of outcrops of Eocene rocks above the 'Great Limestone' inliers of Rajouri-Riasi areas. These consist of a basal zone of laterite succeeded by grey and green pyritous and carbonaceous shales and Nummulitic Limestone. The shales overlying them contain workable coal seams, which are more or less crushed and anthracitic.

New vertebrate fossils of *Brontotheres, Raoellid Artiodactyls* and *Cetaceans* are reported from the upper part of Subathu Group (Middle Eocene) that are exposed in the Kalakot-Metka-Moghala inliers of Rajauri district. The Eocene *Artiodactyls* of India do not resemble contemporary forms from contiguous regions and are probably endemic to the subcontinent.

Kashmir: Eocene rocks of Kashmir comprise dense jaspery quartzites replacing limestone, carbonaceous and pyritous shales, grey calcareous shale and fossiliferous limestones, and unfossiliferous red, purple and green shales with sandstone bands, occupying the precipitous slopes and spurs. These overlie the Triassic limestone in the Uri area and form a recumbent anticline.

Kargil: Eocene limestone, highly shattered by shear planes and forming crest lines of hill ranges, extends from west of Kargil in a south-easterly direction for a distance of about 300 km along the upper Indus valley. All along, the Nummulitic Limestone overlies conformably the Cretaceous flysch sediments.

The Ladakh Molasse Group comprising of conglomerates, sandstones and shales exposed in Wakka Chu near Kargil is divided into Kargil, Tharumsa and Pashkyum Formations (Fig.10.4). All the characteristics of these formations are presented in Table 10.6. The Kargil Formation is tentatively assigned to Upper Oligocene-Eocene age and the Tharumsa Formation to Eocene-Miocene age.

Himachal Pradesh

In the Lesser Himalayan tectogen, Paleogene represents a major transgressive phase of flooding in the Proterozoic and Lower Cambrian rocks.

Table 10.5. Palaeogene formations of the sub-Himalayan belt and Sindhu-Tsangpo valleys (after Valdiya, 1998, p.75)

Age										
Epoch	Time Range (m.y. ago)	Sindh-Salt Range	Potwar-Jammu	Himachal-Kumaun	Nepal	Arunachal Pradesh	Assam-Indo-Myanmar Range		Upper Sindhu Valley	Myanmar
Early Miocene	– 16.2 –	Gaj	Murree	Kasauli	Dumri		Surma	Bokabil Bhuban	Kailas Congl. (Kargil)	Pegu
Oligocene	– 23 –	Nari		Dagshai			Barail	Renji		
Eocene L	– 30.5 –	Kirthar	Chharat Lst.	Subathu	Bhainskati	Yinkiong		Jenam		
Eocene M	– 34 –							Laisong		
Eocene E	– 39 –	Laki	Hill Lst.				Jaintia/ Disang	Kopili	Indus Fm.	Yaw Podaung
Paleocene	– 53 –							Sylhet		Tabyin
		Ranikot		Bansi-Kakara	Amile	Abor		Lakadong (Langpar) Therria		Laungshe Paunggyi
	– 65 –									

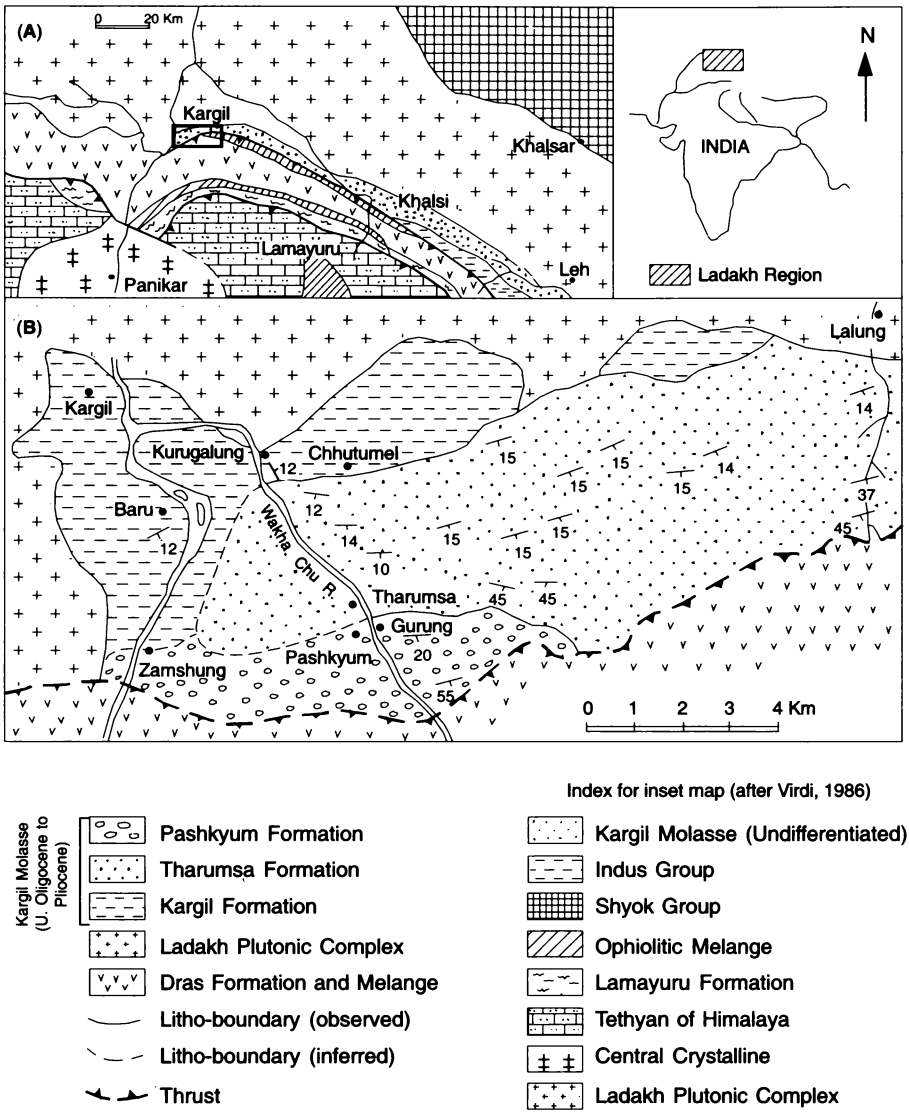


Fig.10.4. (**A**) Regional setup and various lithotectonic units of Kargil area. (**B**) Detailed geological map of the area (source: Rohtash Kumar and Virdi, 1997, p.677).

Preceding the Paleocene-Eocene transgressive phase, there was an onset of wet tropical climate, which is reflected in the formation of pisolitic laterite beds on the pre-Paleogene rock surface.

The Paleogene formations occur in two distinct structural zones.

(i) Kakara Formation, mainly representing Paleocene or Paleocene-Lower Eocene, occurring as outliers over diverse pre-Paleogene Formations.

(ii) The foothill range of Paleogene belt of Sirmur Group comprising

Table 10.6. Characteristic features of Kargil Molasse (modified after Rohtash Kumar and Virdi, 1997, p.676)

Formation	Lithology	Sedimentary Structures	Palaeocurrent	Fossils	Environment	Remarks
Pashkyum 900 m	Purple mudstone and greyish green fine to coarse sandstone in the lower part and conglomerate inter-bedded with purple mudstone	Imbrication and trough stratification	From SW and S	Vertebrates, fresh water molluscs, plants, etc.	Sandy braided to alluvial fan	Exposed in the southern and SW part and overlaps both Kargil and Tharumsa Formations
Tharumsa 700 m	Thick, multistoried grey sandstone and massive grey mud-stone with sub-ordinate amount of marl and conglomerate	Trough cross-stratificatiom imbrication and ripple marks	From NE and East	Fish remains, fresh water molluscs, Charophyte and plant remains	Gravity braided stream to sandy braided stream, Locally meandering and lacustrine deposits	Overlaps the Kargil Formation towards west and overlapped by the Pashkyum Formation in the south
Kargil 200 m	Conglomerate, greenish grey sand-stone and purple mud-stone with marl	Imbrication and trough cross-stratification	From SW and West	Vertebrates, fresh water molluscs and plant remains	Alluvial fan to braided stream with lacustrine environment	Overlapped by Tharumsa in the east and by the Pashkyum in the south and southeast

Subathu-Dagshai-Kasauli sequence, ranging mainly from Lower Eocene to Lower Miocene bordering the Lesser Himalayan pre-Paleogene structural belts along their southern margin.

Kakara Formation: The name 'Kakara' has been adopted in preference to 'Subathu' to highlight the difference in facies, total fossil assemblage, basement position, structural position and restricted range of sedimentation. It is also to distinguish this facies from the predominantly Eocene Subathu Formation of the main foothill belt (Table 10.7) of the Paleogene formations of the Sirmur Group (Table 10.8). This includes Subathu, Dagshai and Kasauli Formations occurring within the foothill Paleogene belt from the rivers Ravi to the Yamuna in the Himachal Himalaya.

The Kakara Formation comprises a basaltic pisolitic laterite (or even a bauxite), followed by a sequence of quartz arenite, variegated shales and massive to thin bedded limestone. It has been assigned a Thenetian to Early Ypresian age (uppermost Paleocene to Lower Eocene) on the basis of fossil content. The fauna is considered to suggest an open marine to shallow marine brackish water basinal condition.

Subathu Formation: At Subathu town, the formation has at the base paleosol of underlying formations, succeeded by a seam of impure coal. Some are of the view that the three formations of Subathu, Dagshai and Kasauli represent intertonguing units and facies changes, whereas for some, the change in lithology may be due to structural control. The litho- and biostratigraphy of Subathu is presented in Table 10.7. Member B in Subathu (Table 10.8) contains freshwater gastropods and divergent terrestrial vertebrates.

Subathu Formation represents the oldest rocks of the Paleogene succession in the Lesser Himalaya of Himachal Pradesh. Palynological assemblage at Bilaspur consists of dinocyot, spore, pollen, fungal and algal remains. Besides foraminifera, nannoplanktons, ostracodes, mollusca and bryozoans have been recorded from this formation. Among the vertebrates *Istherium subathuensis* is considered to represent the oldest Tertiary mammal known so far from the Indian subcontinent. Oldest global record of whales at about 53 Ma is from the Subathu Formation of Himachal Pradesh. The taxon *Himalayacetus* suggests even an older diversification time for whales. The micro-floral assemblages are characterised by the predominance of the *Thallophytes*, especially the class *Dinophyceae* represented by dinoflagellates.

Subathu represents mainly shallow marine to partially brackish water environment. It is assigned Lower to Middle Eocene on the basis of larger foraminifera and nannoplanktons. It is estimated to range from 61.5 to 43.7 Ma and that of Dharamsala Formation from 35.5 to 11.5 Ma. In view of

Table 10.7. Stratigraphy of Subathu in the Himalayan foot-hills (source: Sastri, 1988, p.414)

AGE	LITHOSTRATIGRAPHY			BIOSTRATIGRAPHY		
	EARLY GSI WORK	Raiverman (1976)	A. Ranga Rao (1979)	Datta (1965)	Soodan (1979)	Govindan (1980)
MIOCENE	DAGSHAI	SUBATHU: RED FACIES	DAGSHAI (INCLUDES RED FACIES)			
OLIGOCENE						
LATE EOCENE			SUBATHU: UNIT B (PART OF RED FACIES)	NUMMULITES BEAUMONTI ZONE		
MIDDLE EOCENE				NUMMULITES STRIATA ZONE		NUMMULITES AFF. BEAUMONTI POORLY FOSSILIFEROUS NUMMULITES URANENSIS ASSILINA AFF. EXPONENS
EARLY EOCENE	SUBATHU	SUBATHU: GREEN FACIES	SUBATHU: UNIT A (GREEN FACIES)	ASSILINA SUBSPINOSA ZONE	NUMMULITES SUBATACICUS	ASSILINA AFF. MAJOR NUMMULITES AFF. ATACICUS
					LOCKHARTIA HUNTI VAR PUSTULOSA	ASSILINA LAMINOSA - LOCKHARTIA TIPPARI
					DICTYOCONOIDES FLEMINGI	LOCKHARTIA CONDITI - ROTALIA TROCHIDIFORMIS
PALEOCENE				DICTYOCONOIDES FLEMINGI ZONE		

Table 10.8. Lithostratigraphic classification of the Sirmur Group (after Srikantia and Bhargava, 1998, p.117)

Formation	Member	Lithology	Thickness (m)
Kasauli		Massive sandstone, subordinate shale	1250
Dagshai	Pabo	Alternation of sandstone and clay	1200
	Chimnun	Red and purple claystone with subordinate siltstone	700
Subathu	B	Red, green and indigo blue coloured mudstone, shale and quartz arenite	12-90
	A	Green shale, foraminiferal limestone and oyster marls, quartz arenite, local carbonaceous shale, calcareous sandstone	160

? Kakara

_____ Base generally not known _____

the small thickness of these sedimentary sections, it is evident that the rate of sedimentation may have been very slow.

Dagshai Formation: This overlies the Subathu with a gradational contact. Recent palaeontological studies seem to indicate perfect biochronological continuity from Subathu to Dagshai with no hiatus between them. Gypsiferous nodules and lenses are seen in the lower and middle part. It is sparsely fossiliferous, consisting mainly of plant impressions, trace fossils of worm-tracks and burrows. Flora is indicative of moist to dry tropical forest. The deposition of Dagshai is variously considered to have taken place in terrestrial regime akin to Indus-Ganga Plain and shallow marine environment in estuarine complex. The contact between the Dagshai and the succeeding Kasauli, though gradational, is also marked by tephra, which is considered to be Upper Oligocene to Lower Miocene. The Dagshai is assigned to a Late Eocene to Oligocene age.

Uttarakhand

In Uttarakhand, the Subathu has the status of a formation. Good sections of the Subathu Formation are encountered in Garhwal synform at Nilkanth, Tal *nadi* at its confluence with the Bedasini river to Koh valley, Dugadda area and at several places along Risikesh-Devprayag road between Mala Gunti and Kauriyala.

Fossils:Forams*:* *Nummulites atacicus, Assilina daviesi, A. laminose, Nummulites* cf. *globulus* , *Operculina* cf. *patalensis,*

Nannoplanktons: *Reticulofenetra dictyoda, Discoaster lodoensis*
Bivalves: *Venericardia* cf. *mutabilis, Trachycardia* sp., *Pelecycora* sp., *Ostrea* sp.
Trace fossils: *Thalassinoides, Palaeophycus, Planolites*

The foraminiferal and nannoplankton assemblages favour a time range from Lower to Middle Eocene for Subathu Formation.

Northeastern Region

Around Middle Cretaceous, when collision between the oceanic extensions of the Indian Plate with those of its neighbours started, the sediments of the shelf areas and the collision zones were several thousand kilometres apart. But as the continental part of India closed in, this gap slowly decreased, so that by around Late Eocene the shelf and the peripheral tectonic basins may have come close to each other.

In the compressional regime provided by collision (Fig.10.5) the following zones have developed:

- a shelf zone adjoining the landmass of the subducting plate,
- a slope leading off from the shelf to the basin deep,
- the basin deep where concurrent sinking of the basin floor permits most of the sediment to take place, and
- a mobile rim, which is more immediately affected by the collision zone mountain building for its tectonic pattern and sediments.

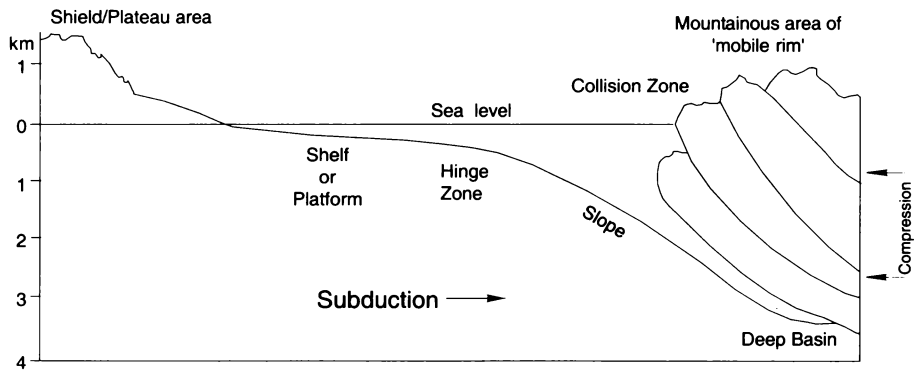


Fig.10.5. An idealised profile of different segments of a basin on the subducting plate near collision zone. Mountainous topography identifies 'Mobile Rim' at surface (after Das Gupta and Biswas, 2000, p.48).

Assam and Meghalaya

The Tertiary stratigraphy of Assam, Meghalaya and the adjoining regions reflect the interaction of tectonics, varying basin configuration and facies

changes. At any given time, there are different types of sediments in different basins, not necessarily connected, and receiving their sediments from different provenances. Whereas the lithology and sequence of strata are well established and relatively dated in different sections based on the study of surface and subsurface data, correlation between them has not been quite easy since many of the sediments are unfossiliferous and lack invertebrate zonal fossils. It is because of this, in the early days of investigations in this region, heavy mineral studies were resorted to but subsequent studies on microfossils provided better correlation (Table 10.9). In this section, stratigraphic sequences fairly well established of the Paleogene in certain regions, are given with their faunal and floral contents.

Early continental edge or shelf sediments have good development in both the Therriaghat and Borghat-Narpuh sections near the southern edge of the Shillong Plateau. The sequence observed in the latter sections is as follows:

Eocene:	Lakadong, Umlatodoh, Nurpuh, Prang, Kopili	~850 m
Palaeocene:	Langpar and Therria	~245 m
Cretaceous:	Mahadek	~230 m

In Therria area the K/T boundary falls in an ecologically homogeneous marine sequence about 11 m below the top of the Mahadeo Formation (Table 10.10). This boundary is taken at the extinction level of *Globotruncana stuarti.*

Occurrence of extensive conglomerate in the Langpar Formation above the Cretaceous sediments indicates a definite time gap between the two.

Late Cretaceous-Tertiary sediments together with underlying Sylhet Trap and the Precambrian granites/gneisses are exposed along the southern fringe of Meghalaya Plateau. The huge pile of sediments is dissected by E-W and NNE-SSW striking faults. The sedimentation of this pile is controlled by basin transgression and regression and not by the Dauki or other faults. Dauki fault being post-Kopili (post-Eocene) in age, could not have acted as a growth fault during the deposition of these Late Cretaceous-Paleogene sediments. Dauki fault is a major E-W striking fault system extending for 250 km or more in the southern part of Meghalaya. The throw of this regional fault system is to the tune of several hundreds of metres.

Strata belonging to Eocene occur practically in all the sections of Tertiary basins in and around Assam. They are all essentially made up of sandstones, shales and limestones. Foraminifers and palynofossils have been mainly used in the correlation of strata. Table 10.9 presents the distribution of palynofossils in the different stratigraphic units in Mikir Hills, Dhansiri valley and Upper Assam. Foraminifers were found equally useful and certain assemblage zones were established in Dhansiri valley.

Table 10.9. Composite palynostratigraphy of Mikir Hills, Dhansiri valley and Upper Assam (modified after Deshpande et al. 1993; courtesy ONGC) (source: Das Gupta and Biswas, 2000, p.116)

Age	Formation/ Group	Characteristic Palynoflora	Palyno Zone	Palaeoenvironment
Plio-Pleistocene	Moran Group	*Scabratriletes* sp. *Pteridacidites* sp. *Compositoipollenites* sp. *Jugalanspollenites* sp. *Umbelliferaepites* sp.	VIII	Freshwater, fluvial
Miocene	Tipam Group	*Acanthotriletes* sp. *Quercoidites* sp. *Pinuspollenites* sp. *Ilexpollenites* sp. *Myricipites dubius*	VII	Fluvial
	Boka Bil Formation	*Deltoidospora* sp. *Lygodiumsporites* sp. *Ericipites scabratus* *Dissacate* sp. *Veryhachium* sp.	VI	Marginal marine
Oligocene	Barail Group	*Meyeripollis noharkotensis* *Spinizonocolpites* sp. *Longapertites* sp. *Zonocostites romonae* *Cupulliferoipollenites* sp.	IV	Swampy and marshy
Late Eocene	Kopili Formation	*Polycolpites* sp. *Couperipollis* sp. *Marcolporites* sp. *Palmaepollenites* sp. *Pellicieroipolllis* sp. *Michrystridium* sp.	III	Near shore to coastal
Middle Eocene	Sylhet Formation	*Psilodiporites hammeni* *Meliapollis* sp. *Liliacidites* sp. *Tricolpites reticulatus* *Dinoflagellate* sp.	II	Shallow marine
Palaeocene to E. Eocene	Tura Formation	*Dandotiaspora telonata* *Lakiapollis* sp. *Schizaeoisporites* sp. *Clavapalmidites* sp. *Proxapertites* sp.	I	Continental
Mid to Late Cretaceous	Moabund Formation	*Araucariacites* sp. *Callialasporites* sp. *Alisporites* sp. *Classopollis* sp. *Cycadopites* sp. *Dinoflagellate* sp.	K_2	Coastal to marginal marine
Cretaceous	Bamangaon Formation	*Cicatricosisporites* sp. *Cingulatisporites* sp. *Callialasporites* sp. *Classopollis* sp. *Microcachryidites* sp.	K_1	Continental

Note: The Zone V palynoflora which characterises Bhuban Formation in Cachar-Tripura wells is absent in these areas

Table 10.10. Section in Um Sohryngkew River near Therria exposing an uninterrupted succession of Late Cretaceous - Paleogene strata (after Pandey et al. 1992)

Group	Formation	Thickness	Age
Barail		100+ m	Oligocene
	Kopili	100+ m	Late Eocene
Sylhet	Prang Umlatdoh Lakadong Therria Langpar	145 m 100 m 100 m 100 m 50 m	Late Eocene Middle and Late Eocene Late Paleocene - Early Eocene Middle Paleocene Early and Middle Paleocene
- - - - - -	~Unconformity~~	- - - - - -	- - - - - - - - - - - - - - - -
Meghalaya	Mahadeo Um Sohryngkew	50 m 250 m	Late Cretaceous - Early Paleocene Late Cretaceous
- - - - - -	~Unconformity~~	- - - - - -	- - - - - - - - - - - - - - - -
	Jurassic (basalt ?)		

The Barail Group, belonging to Oligocene, has been studied in many outcrops in conjunction with borehole data, in the northeastern region. Their main characteristics and distribution are briefly given below:

1. Barail Group in the Barail Range: The Barail Range has two topographic features, separated by the Jatinga-Kayang valleys. The northern feature is really an easterly continuation of the Shillong Plateau. The Barail strata here have gentle dips and form part of the shelf sequence. The southern feature lies on the basinal side of the Disang Fault. It forms part of the northern outcrops of Sylhet and Cachar.

Renji	Sandstone	up to 1000 m
Jenam	Shales, Sandstones	1000 to 1200 m
Laisong	Sandstones, Shales	1000 to 2400 m

The available palynological information suggests an Oliogocene age.

2. Barail Group east and south of Barail Range: Barail of the type area continues north-eastwards up to Japvo and thereafter swings southwards forming a 30-40 km wide belt of hill features in west Manipur, east Mizoram and the Chin Hills. The Barail in this belt is close to the collision zone and forms virtually the mobile rim (see Fig.10.5) of its depositional basin.

3. Barail Group in the zone of Schuppen: Northeast of Haflong, an imbricate zone of upthrust sediments separates the main Naga-Patkai mountain

mass from the Shillong-Mikir hills and the Dhansiri-Brahmaputra valleys. From its fish scale pattern of the faults, this is called a zone of schuppen. Its southeastern limit is the Disang Thrust and in some places its local offshoots - the Yah and Sinyang Thrusts. Its northwesterly limit is a composite group of faults, collectively named for convenience – the Naga Thrust. Rough estimate of the thickness of the Barail in this zone is around 5000 m. Most of these would be geographically in Nagaland.

4. Barail Group in the Shelf zone: These comprise the following: (a) a thin development of sandstones and shales unconformably overlying the Kopili formation in the Garo hills, (b) a thicker development of sandstones with some shales mapped as Laisong/Undifferentiated Barail, at the southeast margin of the Shillong Plateau and (c) a variable thickness of sandstones, shales, carbonaceous shales and thin seams of coal, on the south-easterly sloping shelf zone in the Dhansiri-Brahmaputra valley.

In Assam, the end of the Oligocene period was marked by a gentle differential movement, as a result of which the Shillong Plateau and Mikir hills were elevated to a higher level. Antecedent streams comprising mainly the Brahmaputra and its tributaries (Subansiri, Manas and Santokh) became active and reached the Early Miocene coastline close to latitude 26°N.

In the Assam-Bangladesh region in the eastern sector, the major Himalayan uplift is marked by the presence of a regional unconformity at the Oligocene-Miocene boundary. The Surma Series (Lower Miocene) of Assam indicates deposition in a fluvial to brackish environment from north to south, thickening towards the south and the southeast.

Bulk of hydrocarbons discovered so far is within the Barail Formation (Oligocene) and Tipam Formation (Miocene) in the Assam shelf zone of the eastern part of Upper Assam basin. Subsequent discoveries of oil and gas fields within Paleocene-Lower Eocene rocks in and around the hidden basement ridge near Dibrugarh have opened up a new chapter for exploration within the sequences in the unexplored/inadequately explored areas in Assam shelf zone.

Arunachal Pradesh

In Arunachal Pradesh, the Cenozoic is represented by four sequences of (i) Yinkiang Group, (ii) Siwalik Supergroup, (iii) Older Alluvium and (iv) Newer Alluvium. The last two do not seem to have a distinct stratigraphic status now. The Yinkiang Group extending from Upper Paleocene to Lower Eocene age is made up of Geku and Dalbuing Formations.

The Geku Formation, overlying the Abor Volcanics unconformably, is

made up of purplish and grey welded tuffs (? ignimbrite) followed by micaceous siltstone and purple and green shale (1200 m). This is followed by dark green to grey vesicular amygdaloidal mafic volcanics (650 m) and purple green shale (424 m). In the middle part of the succession, plant fossils were discovered. Tentatively the formation is assigned to Paleocene.

The Dalbuing Formation, conformably following the Geku Formation, is made up of quartzite, sandstone and purple and nodular grey shale containing plant fossils, pteridophytic spores, pollens of gymnosperm and angiosperm and phytoplanktons. Thin bands of grey nummulitic limestone associated with shales have yielded phytoplanktons and foraminifers *Nummulites atacious, N. lahiri, N. obtusus, Assilina dandotica, A. granulosa* etc. of Early Eocene to Middle Eocene, comparable to the assemblage found in Subathu Group in northwest Himalaya.

The Disang Group of rocks occurs in the southeastern part of Arunachal Pradesh in the Naga-Patkai Range. The Lower and Upper Disang Formations contain impressions of dicotyledonous plant leaves.

In the Barail Group mapped in Naga-Patkai Ranges, the three subdivisions have been named as Naogaon, Bargolai and Tikat Parbat Formations. On the basis of microfauna and palynofossils, the Barail Group here is assigned to Oligocene age.

Tamil Nadu

The Cretaceous succession in Tiruchirapalli area is unconformably overlain by a thick carbonate sequence extending from Vellar river in the north to Kavanur in the south, over a strike length of 26 km, as disconnected outcrops exposed around Niniyur and Sendurai, northeast of Ariyalur. It is about 70 m thick. Lithologically, this unit is divisible into lower fossiliferous limestone, middle crystalline shelly limestone and upper argillaceous gritty nodular limestone collectively known as Niniyur Formation. Earlier, designated as Niniyur Stage, it was separated from the Ariyalur Stage and considered Danian in age. But recently some of the sediments above the Kallamedu Formation in the Ariyalur Group is separated and named as Niniyur Formation (Table 8.7).

A rich algal flora was identified in the Niniyur among which *Parachaetetes asvapathi, Archaeolithothamnium lugeoni, Dasiclodella savitrae, Acicularia dyumatsenae* are important, besides the planktonic foraminfer *Globorotalia* and benthonic foraminifera *Quinqueloculina, Triloculina, Cibicides* and *Thalmonnata.* The microfauna of this stage indicated a Paleocene age. Recently ostracodes have also been found in the Niniyur Formation and identified in different lithounits. Common ostracode species of Niniyur Formation in the

three adjoining areas of Trichy, Vriddachalam and Pondicherry are *Bairdoppilata talukdarai* and *Xestoleberis rupnarayanalurensis*. The algae, cephalopod (*Nautilus danicus*), gastropods (*Nerinea*), foraminiferids and ostracodes suggest an Early Paleocene age. Beds equivalent to Niniyur Formation are seen in Vridhachalam and Pondicherry areas as well. The sediments are considered to have been laid down in a shallow marine to slightly brackish water environment with restricted passage to open sea. The carbonate beds are presently mined for cement industry.

Kerala

From a borehole drilled at Ambalapuzha in Allepey district, between the depths of 400-571 m, characteristic pollen genera including *Palmaepollenites, Couperipollis, Proxapertites, Meliapollis, Striacolporites, Retistephanocolpites* were identified. A larger foraminiferal species, *Actinosiphon* sp. recorded from subsurface at Ambalapuzha at 454 m confirms the presence of Paleocene-Eocene sediments on the onshore Kerala sedimentary basins. In the Cochin basin offshore, off Kochi, sediments of Tertiary overlie Deccan basalts.

Andaman and Nicobar Islands

The Baratang Group/Formation is made up of grey shales, siltstones and grey impure limestones. These lie unconformably in some sections over plutonic and volcanic rocks of the Serpentine Group. These contain foraminiferal assemblage referable to Paleocene.

The rocks belonging to the Port Blair Group, more than 3000 m thick, cover a greater part of Andaman and Nicobar islands (Fig.8.18). These overlie the Baratang Group/Formation with an unconformity. A radiolarian assemblage of Middle Eocene age is recorded from these sediments in South Andaman Island, constraining the timing of the tectonic processes of the region.

NEOGENE

INTRODUCTION

Neogene represents one of the most crucial periods of the geological history of our planet. Tethys was destroyed concomitant with the uplift of the Himalaya and spreading of the Indian Ocean during this period. The Middle Miocene uplift of the Himalaya was one of the strongest orogenic impulses that also initiated the southward dispersal of coarse clastics, sands and mud, which characterised the older formations of the Siwalik Group. This period marks the

crucial stage in the development of global climates and the evolution of *Homo sapiens*. The Kasauli Formation in Himachal Pradesh and Murree Formation in Jammu (Aquitanian-Burdigalian) mark the onset of the first sedimentary contribution from the Himalaya. A tentative correlation of Neogene rocks of the Indian subcontinent is presented in Table 10.11. A set of stages suitable for Miocene-Pliocene deep marine sediments has been introduced based on planktonic foraminifera collected from the Andaman-Nicobar islands (Table 10.14).

Table 10.11. Stratigraphic correlation of Neogene sediments of the Indian subcontinent (time scale after Berggren and Van Couvering, 1974) (source: Sahni and Mitra, 1980, p.41)

<table>
<tr><th colspan="3" rowspan="2">AREA / AGE</th><th colspan="2">PAKISTAN</th><th colspan="6">I N D I A</th><th rowspan="2">BURMA</th></tr>
<tr><th>SIND & BALUCHI-STAN</th><th>POTWAR PLATEAU</th><th>SIMLA & GARHWAL</th><th>JAMMU & KASHMIR</th><th>KUTCH</th><th>KATHIA-WAR</th><th>ASSAM</th></tr>
<tr><td colspan="3">PLEISTOCENE</td><td colspan="2">Older Alluvium
Boulder Congl. Stage
Pinjor Stage</td><td colspan="2">Karewa Formation</td><td colspan="2">Porbandar Limestone</td><td>Older Alluvium
Dihing Series</td><td></td></tr>
<tr><td rowspan="2">PLIOCENE</td><td>PIACENZIAN</td><td rowspan="2">Upper Manchar</td><td colspan="2">Tatrot Stage
Dhok Pathan Stage</td><td colspan="2" rowspan="2"></td><td>Kankawati Series</td><td>Dwaraka Beds</td><td></td><td rowspan="3">Irrawaddy System</td></tr>
<tr><td>ZANCLIAN</td><td colspan="2">Nagri Stage</td><td>Piram Beds</td><td>Dupitila Series</td></tr>
<tr><td rowspan="6">MIOCENE</td><td rowspan="4">MIDDLE & UPPER</td><td>MESSINIAN</td><td rowspan="4">Lower Manchar</td><td colspan="3">Chinji Stage</td><td rowspan="3">Vinjhan Stage</td><td rowspan="3">Gogha Beds</td><td rowspan="3">Tipam Series</td></tr>
<tr><td>TORTONIAN</td></tr>
<tr><td>SERRAVALLIAN</td><td colspan="3" rowspan="2">Kamlial Stage</td><td rowspan="3">Upper Pegu System</td></tr>
<tr><td>LANGHIAN</td></tr>
<tr><td rowspan="2">UPPER</td><td>BURDIGALIAN</td><td>Upper Gaj</td><td rowspan="2">Murree Formation</td><td rowspan="2">Kasauli Formation</td><td rowspan="2">Murree Formation</td><td></td><td>Upper Gaj</td><td rowspan="2">Surma Series</td></tr>
<tr><td>AQUITANIAN</td><td>Lower Gaj</td><td>Aida Stage</td><td>Lower Gaj</td></tr>
</table>

FAUNA AND FLORA

Fauna

The Tertiary rocks of both the western and eastern coasts of India are characterised by assemblages of sharks, rays, teleosts, turtles, crocodiles, sirenians and cetaceans. Further, the presence of 30 to 40% of species of the Miocene marine vertebrates and molluscs in the present Indian Ocean points to the existence of a stable environment.

About 100 mammalian species belonging to 52 genera have been reported from various parts of the subcontinent mainly from the north-central Pakistan

and the coastal Tertiary deposits. The first mammal to be reported from Kutch district was *Dicoryphochoerus*. From Tertiary rocks of Kutch, mammalian coprolites have been reported. Marine mammals are known from Piram Island in the Gulf of Cambay, by a single delphinid cetacean. Its affinities lie with the common dolphin- *Delphinus*. The widespread occurrence of *Archaias malabaricus* in Sri Lanka, Quilon (Kerala) and Kathiawar (Gujarat) suggests a contemporaneity (probably Burdigalian) for the fauna. Mammals show an intermixture of African and southern Russian species as well as some endemic forms. It is inferred that, apart from minor eustatic transgressive phases, the palaeoecology along the shorelines of the Peninsular Shield has altered little since the Early Miocene. Early Miocene fauna of the open sea type was recorded from Main Boundary Thrust Zone from Tista river section in Darjeeling foothills (in West Bengal), thus constraining the timing of final withdrawal of Tethys.

In view of its chronostratigraphic value, several contributions chiefly on planktonic foraminiferal distribution and taxonomy have been published from different regions of the world. Calcareous larger foraminiferids constitute dominant faunal element in it besides other groups. The East Indies Letter Classification has provided a broad framework of larger foraminiferal association in the Tertiary with 'stages' designated as Ta (older) to Th (younger), which are fairly applicable in the Indo-West Pacific Province. Recently a zonal scheme, based on Tertiary larger foraminiferids from Indian basin integrating with standard planktonic zone and Letter Stages, has been brought out by Govindan (2003).

Flora

With development of angiosperms, the flora became an important component of a major part of the rocks in Middle and Upper Miocene. It comprises about 60 plant families of which over 50% are angiosperms. Mega-floral remains comprising leaf impressions and petrified woods are reported from Kangra and Kalka in Himachal Pradesh, Mohand and Tanakpur in Uttaranchal, Darjeeling, Tripura, and Mikir hills in Assam and in Villupuram district in Tamil Nadu. While the prevalence of *Dipterocarpus* throughout the subcontinent during a major part of the period suggested tropical and rainforest condition, the end of the period is marked by its complete extinction. The oldest known preserved diatoms, both marine and fresh water, in the country, have been reported from the Miocene beds. In the latter part of Miocene, coal and lignite development was restricted to the eastern, southern and southeastern sectors corresponding to areas having a hot, humid, tropical climate. Coal is reported from Upper Assam, the Mkum area, Naga, Patkai and Singpho Hills,

Darjeeling. Lignite occurs in Darjeeling, Bengal Basin, Godavari Alluvium, and Neyveli in Cuddalore district, Tamil Nadu, Pondicherry, Kochi and Thiruvananthapuram in Kerala and in Gujarat.

STRATIGRAPHY

Gujarat

Mainland: The Dinod Formation (of Late Eocene age) exposed around the villages Nandev, Dinod and Dungri is unconformably overlain by the highly ferruginous sandstone and agate conglomerate of Babaguru Formation. Based on its stratigraphic position the latter is tentatively considered to be Lower Miocene. Kand Formation, around the village Kand (Kond), unconformably overlies the Babaguru Formation (200-300 m) and is made up mainly of calcareous sandstone with occasional conglomerate, clay, marl and thin fossiliferous limestone, containing microfossils. The megafossils include lamellibranchs (*Ostrea, Pecten, Cardita*), gastropods (*Turritella, Conus*), echinoid spines, cirripedia (*Balanus*), fish teeth, and calcified fossil wood and leaf impressions. On the basis of these fossils and the presence of foraminifers like *Lepidocyclina, Miogypsina* and *Austrotrillina,* a Lower Miocene (Burdigalian) age has been assigned to this formation.

Overlying the Kand Formation is the Jhagadia Formation (200 m) made up of light grey sandstone and pebble to cobble conglomerate. They are devoid of fossils and their lithological characters point to a continental fluviatile depositional environment. Good exposures are met with near the villages of Ratanpur and Jhagadia. Since in the subsurface this formation is overlain by Broach Formation (300 m) of Pliocene age (based on its fossil content – foraminifera), a Middle Miocene to Lower Pliocene age is assigned to the Jhagadia Formation. Broach Formation consists of red brown claystone, sandy claystone and sandstone, a sequence deposited in a shallow marine oxidizing environment. A Pliocene age was suggested based on stratigraphic position. This formation is overlain by Jambusar Formation.

Saurashtra: Francis Fedden first investigated the Neogene rocks outcropping along the western and southern coast of Saurashtra. From Bhavanagar to Okha Rann, marine Miocene rocks named the Gaj Formation, occur as a series of discreet outcrops. This is divided into Ratanpur, Bhumbli and Kuda Members. The type locality is at Gogha. At many places this formation is overlain by miliolites. These have an earthy yellow appearance in contrast to the red and brown coloured landscape of the laterite underlying them. The formation contains a variety of mega- and microfossils. The microfauna is

distinguishable from that of the overlying Dwaraka Formation by the presence of *Miogypsina* and *Nephrolepidina* and the abundance of ostracodes. The ostracodes point to a Lower Miocene age. In the Ghoga area, Piram Beds, well developed on the offshore island of Piram, in the Gulf of Cambay (Khambhat), overlie the Gaj Formation. The rock sequence consists mainly of a number of hard conglomerate beds alternating with silty sandstones and clay. The formation has yielded a large variety of mammalian fossil bones of proboscidia, perissodactyla, artiodactyla and reptilian fossils of chelonia. The overall characteristics of the Piram beds suggest fluvial deposition. The drifted mammalian bones and the mud-cracks in the clays, diagnostic of tidal flats, point to the deposition of these beds in a tidal estuarine environment. Fossil evidences indicate Upper Miocene to Lower Pliocene age. The Dwaraka Formation occupies a major portion of Okha area in northwestern Saurashtra. These form a long line of imposing escarpments and cliffs along the eastern flanks of the Okha Rann and are essentially made up of silty clays and arenaceous foraminiferal limestone. The cliffs at Dwaraka, the famous pilgrimage centre, are about 6 to 8 m high and the rocks contain abundant shelly fragments. The age assigned to this formation ranges from Miocene to Pliocene.

Kutch: The Neogene rocks of Kutch, found along the western and southwestern part, are classified into two series; the older Khari Series overlies the Bermoti Series of Paleogene with an unconformity. On the basis of lithology and fauna, this series is divided into a lower Aida Stage and an upper Vinjhan Stage. Aida Stage (though shown as part of Bermoti Series in Table 10.4) is composed of variegated siltstone and contains Lower Burdigalian fossil assemblage. The Vinjhan Stage comprising a variety of larger foraminifera like *Miogypsina, Lepidocyclina, Taberina* etc. is referred to upper Burdigalian age. The fauna bears a typical Indo-Pacific affinity. The deposition of Aida rocks took place in a transgressing sea under tranquil conditions. The environment of deposition was epineritic to neritic. This indicates that the Miocene sea had penetrated very far inland. In fact, offshore exploration in the Arabian Sea and Gulf of Cambay has shown the existence of Lower Miocene beds over 100 km west of the present coastline. This series is overlapping Deccan Trap directly and obviously this marine transgression was the most powerful one in the history of the Tertiary sedimentation of Kutch. The Kankawati Series that overlies the Khari Series is well developed in the coastal plain of southern Kutch around Kankawati river section between Samdhon and Vinjhan. The lower part is mainly made up of micaceous quartzose sandstones, the middle of conglomerates and the upper of grits and sandstones with calcareous nodules. Fossil woods are common near the base of this series.

A few miliolids, foraminifera and ostracoda are found. Probable Pliocene age is suggested for this series.

Jammu and Kashmir

The Oligocene period is not well developed in Kashmir, with the result, the Miocene formation directly overlies the Eocene rocks at most of the places. However, there occurs a molasse type of deposit, which may belong to Oligo-Miocene age. In the Kargil area, the Pashkyum Formation (974 m) overlies the Tharumsa Formation with a faulted contact and consists of purple shales, sandstones and conglomerates. It is thrust over by Dras Volcanics. A Miocene age is assigned to it.

In the Jammu region, Murree Formation has an outcrop width of 35 to 40 km in the northwestern side in Poonch-Kotui section, which narrows down to 10 km in the Rasi Valley. These are very well exposed in Poonch, Rajouri, Batote-Sudmahadev-Basantgarh areas, sandwiched between the Murree Thrust and the Main Boundary Fault.

In Kashmir, the lower part of Murree consists of pseudoconglomerates and clay concretions, which in Poonch area have yielded mammalian fauna with monocotyledonous and dicotyledonous leaf impressions and valves of lamellibranchs. The upper part comprises soft, crumbling coarse micaceous sandstones of pale grey and brown tints and red purple, grey and buff shales. The Murrees are correlated with Gaj Series of Sind in Pakistan, which on fossil evidence, are supposed to be of Lower Miocene age.

Himachal Pradesh

Early Miocene marks the time of the first sedimentary contribution from the Himalayan front. Kasauli sediments, occurring within the Himalayan foothill belt from Ravi to Yamuna rivers, are characterised by decomposed rock fragments, as are the underlying Dagshai sediments. At the end of Early Miocene, the relief in the source area was rejuvenated, resulting in the erosion of still deeper metamorphosed sediments, comprising kyanite schists, garnetiferous mica schists and associated schistose rocks. Rivers discharged their load into a sedimentary basin running transverse to the Main Himalayan axis after a short transport.

The Kasauli Formation comprises sandstone with subordinate shales with a gradational contact with the underlying Dagshai. The contact is marked by a tephra locally (i.e. pyroclastics of a volcano). The alternation of sandstone and shale has produced a distinct geomorphic expression due to differential weathering. The flora in this formation indicates moist to dry tropical forest

environment. Based on *Unio* and palm leaves, an Early Miocene age has been assigned to the Kasauli Formation. Well-preserved fossil flowers were found from Kasauli Formation near Barog. These are significant, as fossil flowers are very rare in the Tertiary sequences of the Himalaya.

Assam

The Surma-Tipam succession, which overlies the Barail Group (Table 10.12), is made up of an assemblage of different lithological types. These vary in thickness depending on their geotectonic location, on the extent of their wedging out against the Barail Group, and on the extent of their passage from one lithological type to the other.

In the vicinity of Assam, these occupy three primary tectonic regions: (*see* Figure 25: Geological map of Assam and surroundings in Das Gupta and Biswas, 2000)

(i) The shelf area extending from the eastern margin of the Shillong-Mikir Plateau to the Dhansiri and Upper Assam valleys, southeast of Basement Spur
(ii) The basinal development in the zone of schuppen, southeast of Naga Thrust
(iii) The Kohima Synclinorium, which opens up into the Surma valley and then extends into the Bay of Bengal

The entire sequence is delimited by two regional unconformities – one at the base and the other at the top, but in between, there is significant lateral variation, from one lithotype to the other.

The Surma (Bhuban and Boka Bil) and the Tipam (Tipam and Girujan) represent basin fills after Barail phase of the Indo-Myanmar collision zone. Surma has marine and brackish water microfauna reflecting basinal deposition. This consequently passes into Tipam both towards the basin margin, as well as, towards the northeasterly head of the filling up gulf. The Girujan Clay represents inland deposition either as a thin rim to the Tipam Sandstone or in a deeper basin of its own, as in northeast Assam. At any point of time, therefore, the Surma was being deposited near the basin centre, the Tipam Sandstone towards the basin margin, and the Girujan Clay further inland. As the basin progressively filled up, depositional area on the Tipam Sandstone moved closer to the centre of the basin. There is thus both geographical and vertical sequencing in the distribution of Surma and Tipam.

The Boka Bil and the Upper Bhuban have yielded some molluscan fossils in a few localities in Garo hills, Tripura and Arakan, suggesting an Aquitanian-Burdigalian (Early Miocene) age. In the basal part, in some of the

Table 10.12. Surma-Tipam succession in Assam and adjoining regions (after Das Gupta and Biswas, 2000, p.65)

Group	Formation	Lithology
Tipam (1200-3000 m) *Nahorkatiya	Girujan Clays (up to 2300 m seen)	Soft mottled clays with patchy variable sand content and occasional thin bands of sandstone and thin streaks of lignite.
	Tipam Sandstones (1100 to 2000 m)	Massive sandstone with some thin bands of shale and occasional bands of mottled clay towards the top. In the upper part, sandstones are rich in heavy minerals.
Surma (0 to over 4000 m)	Boka Bil	Primarily an argillaceous group with some Tipam type sandstones towards the top and bedded sandstones and alternations in the middle and lower parts.
	Bhuban (Upper, Middle and Lower)	Alternating groups of bedded sandstones, conchoidal mudstones and shales. Sandstones poorer in their heavy mineral suite. Slump structures are quite common.
	BARAIL	

*As it is not desirable to have the same name for a group and a formation within it according to the Code of Stratigraphic Nomenclature, the alternate name of Nahorkatiya is suggested for Tipam Group.

sections, the Surma includes some shallow brackish water foraminifera – *Haplophragmoides, Miliammina, Trochammina.* In this region, this fauna is primarily known from the Barail, but it does not necessarily have to be exclusive of the Oligocene.

Arunachal Pradesh

The Tipam Formation in Arunachal Pradesh is exposed north of Disang Thrust, around Bogapani in the Dirang valley, in the upper reaches of Nmpuk river (a tributary of the Burhi Dihing) and Nao Dihing, upstream of Miao. Here it unconformably overlies the Barail Group and is overlain by the Dihing Formation. The Girujan Formation conformably overlies the Tipam Formation and is named after the stream of that name near Digboi. Tipam Formation is endowed with heavy minerals like ilmenite, magnetite, epidote, staurolite, kyanite, hornblende, garnet, chloritoid, zircon, rutile, tourmaline and smaller amount of tremolite, actinolite and zoisite. Absence of enstatite and andalusite in Tipam Formation marks the boundary between Surma and Tipam. Palynological studies indicate the presence of fungal bodies, pteridophytic spores and gymnosperms and angiospermic pollen grains. A deltaic condition

surrounded by marshy vegetation under warm humid subtropical to tropical climate is suggested during the deposition of Tipam Formation.

The Girujan Formation occurring south of the Mishmi thrust is about 2000 m thick in the Kumchai Well in Arunachal Pradesh. The formation shows a sudden increase in staurolite, kyanite, zircon and chromite and decrease in hornblende, epidote and garnet in the heavy mineral assemblage. The palynological assemblage belongs to pteridophytes, microplanktons and angiosperms. These also enclose a few plant fossils.

Unconformably overlying the Girujan Formation is the sequence of soft sandstones with thin clay beds, lignite and conglomerate. These are named Namsang Formation. Dihing Formation unconformably overlies it. The corresponding sequence of the Namsang Formation in Sylhet area is the Dupi Tila Beds.

A large number of fossil woods belonging to dicotyledonous families have been described from Namsang Formation. The flora, which is dominated by the evergreen elements followed by moist deciduous forms, indicates a tropical humid climate with heavy precipitation at the time of sedimentation of the Namsang Formation. These are assigned an age of Upper Miocene-Pliocene. Dhekiajuli/Dihing Formations made up of alternation of conglomerates and blue sandy clays which unconformably overlie the Namsang Formation are assigned a Lower Pleistocene age.

Orissa

The Neogene rocks in Orissa are represented by Baripada Beds. These have a very limited spread out, within a radius of 8 km around Baripada in Mayurbhanj district. Discovered on the Budhabalang riverbed at Molia (3.2 km to the south of Baripada town), the stratigraphy could be worked out from the well section near Chandua as a set of stratified clay and sand with semi-consolidated clay, ferric grit capped by ferruginous soil. At places marly clay or limestone interbands are seen. Significant fossil fauna are *Ostrea* sp. like *Crossotrea gajensis* Vredenburg (index fossil of Lower Miocene), fragments of *Palmaxylon* and *Shoreoxylon*. The Baripada beds extend southward up to south of Balasore with a dip of 4 to 5° due south. A Miocene age is given to Baripada Beds.

The sedimentation started in a near shore shallow marine environment, followed by shallower, warm, moist, marine environment close to the shoreline, such as protected by bay or back reef. This was followed finally by deposition in a warm shallow marine environment near to shoreline, periodically affected by tides and having open sea connection.

Andhra Pradesh

The Rajahmundry Formation occupying about 1100 sq.km in East and West Godavari districts of Andhra Pradesh is bound by Deccan Trap (K/T boundary) at the base and laterite at the top. General trend of the rock units is NNE-SSW to ENE-WSW with 3 to 5° dip towards southeast. Borehole data show that the Rajahmundry Formation in the Eluru- Rajahmundry area is 110 to 390 m thick and it increases in the dip direction. This formation was divided into (i) Rajahmundry conglomerate and sandstone, (ii) Bommuru claystone and Pidungoya sandstone and (iii) Dowleswaram sandstone. A carbonaceous clay and lignite horizon is now recognised in the middle member.

From the clays of Pangadi quarry (lower member) well-preserved dicotelydon angiosperm leaf impressions similar to *Phyllites* sp. of Eocene age are reported. However, palynofloral assemblage in the carbonaceous shale and lignite in the middle member indicates an Early Miocene age. Overall the leaf impressions and the microflora suggest a range from Eocene (?) to Miocene.

Deposition of Rajahmundry Formation was initiated on the weathered surfaces of the Deccan Trap as indicated by the presence of clay horizon with weathered trap pieces. The lower member is considered to have been deposited in a fluvial environment. Later the basin was covered with swamps and marshes leading to the formation of carbonaceous clay and lignite. Towards the end there was landward migration of the shoreline and glauconite-bearing light green sandstone was deposited in shallow marine conditions. Presence of red colouration in the top beds indicates subaerial exposure of clay and siltstone in the culminating phase of Rajahmundry sedimentation.

Tamil Nadu

The detached Cuddalore Sandstone outcrops, now exposed at Pondicherry, Vriddachalam, Ariyalur, Thanjavur and Sivaganga, formerly existed as a continuous sedimentary cover starting from Pondicherry in the northeast to Sivaganga in the southwest. The present disposition is due to extensive removal of the original continuous sedimentary cover by present day streams such as Varahanadi, Ponnaiyar, Coleroon (Kollidam), Vellar, Vaigai etc. The erosion must have been facilitated due to a drop in sea level.

The Cuddalore Formation generally comprises gritty, pebbly to conglomerate, coarse to fine-grained argillaceous sandstone somewhat ferruginised and lateritised towards the top with intercalated clays. In the exposures, the beds exhibit typical fluviatile, lacustrine, flood plain to estuarine characters. The greater part of the sequence, which is concealed by the upper part of the continental sandstones and alluvium, represents true deltaic influence.

The lignite field in Neyveli extends over a distance of 40 km in a north–south direction and is about 10 km wide in an east-west direction. Sands with artesian aquifers, which exert an upward pressure, underlie the lignite seam, varying in thickness from 8 to 22 m. In the earlier days of mining the underground water had to be pumped out, before the lignite was removed. Now the water table has gone down below the lignite bed. Palynological evidence suggests that the lignite in Neyveli is of Miocene age. The report of palynofossils comprising *Cauveripollis, Tricollaraeporites, Cryassoretitriletes, Qyiloni-pollenites* etc. from this bed supports the dating. Further studies on carbonised fossil logs from the lignite as well as silicified fossil tree trunks from the Cuddalore Sandstone also suggest a Miocene age. Some hold the view that it may be of Upper Eocene age. Mineral Exploration Corporation Limited has discovered the single largest lignite deposit with about 17,600 million tonnes reserves further south at Mannargudi (in the subsurface) in Thanjavur district.

About 40 km NNE of Neyveli occur pebbly sandstones with petrified tree trunks near Tiruvakkarai, which is preserved now as a National Geological Monument. The rock is light pink to dirty white in colour, medium to coarse-grained in texture, arkosic and is characterised by well-rounded and mostly oval-shaped quartzite pebbles. The fossil wood is fine-grained. The woody material is angiospermous *(Dipterocarpceae)* and coniferous *(Podocarpaceae)*. On the basis of palaeobotanical evidence these are considered to be Miocene. It will be of interest to note that the petrified angiosperm logs of Cuddalore Sandstone were perhaps the first documented record of any plant fossil in the country in 1782 (Sonnarat). But much later, Warren made the first illustration in an Indian journal of the petrified logs from Cuddalore Sandstone.

Kerala

The Tertiary rocks in the Quilon (Kollam)-Varkala areas are divided into Quilon beds consisting of limestone and calcareous clays, and Warkali beds comprising sandstone and clays with lignite. Recent studies based on borehole data clearly indicate the existence of at least three formations. Rocks of Quilon Formation, having a maximum thickness of 70 m, underlie the Warkalli with a thickness of nearly 80 m. These are underlain by 100 m thick sediments of Vaikom Formation.

Vaikom Formation consists of gravel, coarse to very coarse sand with greyish clay and carbonaceous clay with thin seams of lignite. The lowest unit of this sequence is exposed in the laterite quarries at Vaikom. They overlie weathered crystalline rocks.

The Quilon Formation consists of fossiliferous limestone, sands and clays.

At the type area Padappakara (8°58'N: 76°40'E), a full section of the Quilon Formation is exposed in a cliff section fringing the Ashtamudi estuary. The limestone contains gastropods, lamellibranchs, corals, foraminifers and ostracods. Based on foraminiferal assemblage including *Taberina malabarica*, *Lepidocyclina* (*Nephrolepidina*), *Miogypsina*, Burdigalian (Lower Miocene) age is suggested for this formation.

Warkalli Formation occurring as patches along the coast conformably overlies the Quilon Formation. The type section is located in Varkala, edging the sea shore, 19 km south of Quilon, where it attains a thickness of 60 m, containing, from the bottom, lignite bed (5 m), alum clays (14 m), sand and sandy clays (23 m) and laterite with sandstone masses (18 m). The areal extent of this formation may be around 2000 km^2, extending along the entire coast. These are considered to be shallow water shoreline littoral deposits. The floral assemblage represents a mixture of ecological groups such as low land, fresh water and sandy beach elements. The relative abundance of fungal and fruit remains is indicative of a high organic input environment with a warm humid climate with heavy rainfall during deposition. A Miocene age is suggested.

Availability of extensive borehole data and analyses of the sediments leads to the view that perhaps the Quilon and Warkalli Formations may be even homotaxial. In a revised classification (Table 10.13), the Tertiary rocks are designated as Warkalli Group. Vembanad Formation of Quaternary overlies the Warkalli Group of rocks separated by a horizon of laterite.

Karnataka

A rich palynological assemblage has been recorded for the first time from the Miocene sediments exposed along Kullur-Kavur road, near Mangalore along the west coast of Karnataka. The assemblage is dominated by angiosperm pollen followed by pteridophytic spores. A comparison of the present palynofloral assemblage with those known from the Indian Tertiary sediments shows its close resemblances with the Miocene palynoflora recovered from Quilon and Warkalli beds of Kerala basin.

Maharashtra

Near Ratnagiri along the west coast in Konkan, a deposit of white and blue clays along with sandy and gravely material of about 20 m rests on Deccan Trap. The clays are intercalated with thin carbonaceous seams (lignite). The clay and lignite beds contain fossilized fruits and leaves along with mineral resin and pyrite. These are assigned a Miocene age.

Table 10.13. Lithostratigraphic classification of sedimentary sequence in Kerala (after Raha, 1996)

Period	Formation	Lithology
Quaternary	Vembanad Fm.	Beach sands, alluvium, red (teri) sands, peat beds with semi-carbonised wood, calcareous clays etc.
- - - - - -	— Unconformity - - (marked by laterite)	- - - - - - - - - - - - - - - - - - - -
	Ambalapuzha Fm.	Sandstones, clays, lignites
Tertiary	Quilon Fm.	Limestones, marls, calcareous clays and sands
	Mayyanad Fm.	Sandstones, coarse gravely sands, clays, lignites and carbonaceous clays
- - - - - - -	— Unconformity - -	- - - - - - - - - - - - - - - - - - -
Late Mesozoic	Karruchal Fm.	Hard, compact, ferruginous, gritty sandstones, conglomeratic near base with clay interbeds and arkoses in the upper part
- - - - - -	— Unconformity - - (marked by bauxite)	- - - - - - - - - - - - - - - - - - -
Archaean	Gneisses, granulites and schists	

Andaman and Nicobar Islands

One of the intense episodes of explosive volcanism (volcanic maxima) occurred in Southeast Asia adjoining the Andaman basin during the Early Miocene (20.5-17.2 Ma) and continued until the beginning of the Middle Miocene (15.8 Ma), when activity was moderate.

Archipelago Group succeeding the Port Blair Group/Formation (Table 10.3) represents Miocene to Pleistocene in the Andaman and Nicobar Islands (Fig.8.18). The Archipelago Group is primarily composed of deep-water marine sediments of varying thickness. In the northern region the sediments are predominantly siliceous including numerous volcanic ash layers with subordinate calcareous siltstones, chalk and limestone. Vitric tuff composed of delicately shaped glass shards with variable amounts of microlites is reported from some sections. The sedimentary structures in tuff beds suggest these as products of ash turbidite. In the southern region the strata are predominantly calcareous, composed mainly of a monotonous sequence of mudstones, silty mudstone and minor limestones. These sediments are very rich in foraminifera and other groups of microfossils. Foraminifera proved to be very reliable tool for subdividing the monotonous sequence of this group.

The increased Early Miocene volcanism appears to be genetically linked with the seafloor spreading during the opening of the Andaman Sea. The association of bathyal benthic foraminifera with increased clastics during the Middle Miocene (15.3-13 Ma) appears to be linked with the Middle Miocene (14 Ma) Antarctic ice cap formation and the resultant lowering of global sea level.

Recent stratigraphic and micropalaeontological studies indicate that an almost continuous marine sequence of Late Mesozoic to Pleistocene age occurs on the Andaman-Nicobar islands (Fig.8.18). The planktonic foraminiferal events allow the Late Cenozoic stages of Andaman-Nicobar to be correlated with established deep sea planktonic zones and in turn calibrated to the palaeo-magnetic and radiometric time scales thus enabling to evolve a biomagneto-radiochronology for the Andaman-Nicobar Late Cenozoic sequence (Table 10.14). Because of generally mobile tectonic setting of the Andaman-Nicobar basin, major hiatuses appear to be tectonically activated and are genetically linked with the uplift of the Himalaya.

QUATERNARY

INTRODUCTION

Quaternary is divided into Pleistocene and Holocene epochs and is known for climatic changes. The term Recent, which is not used now, was proposed by Charles Lyell. It is now replaced by the term – Holocene. Quaternary covers a period 1.81 million years and is very important as it provides a link between the geological, archaeological and human history. The Pleistocene, the lower division of the Quaternary, is known for the glaciations interrupted by periods of ice melting, referred to as the interglacial periods. The glacial and interglacial periods varied in duration and intensity and resulted in the advance and retreat of glaciers.

Quaternary is divisible as follows:

System	Series			Geochronology	Magnetostratigraphy
Neogene	QUATERNARY	Holocene		0.01 Ma	Brunhas (Magnetochron 1)
		Pleistocene	Upper Midddle Lower	1.81 Ma	Matuyama (Magnetochron 2)
	Pliocene				Gauss

Plio-Pleistocene boundary has been defined on the basis of evolutionary changes in the fossil biota, particularly the foraminifera, the appearance of

Table 10.14. Comparison of planktonic foraminiferal datum levels between Andaman-Nicobar/ DSDP site 214 and DSDP site 289 (after Srinivasan, 1988, p.21)

Epoch		Andaman Nicobar Marine Stages	Planktonic Foraminiferal Zones Andaman Nicobar/ DSDP Site 214	Important Planktonic Foraminiferal Datums	DSDP Site 289 Srinivasan & Kennet (1981)
Pleisto-cene		SHOMPENIAN	*Gr. truncatulinoides*	← *Gr. tosaensis* LAD 0.6 Ma →	N 23
			Gr. trunca tosa, overlap	← *Gr. truncatulinoides* FAD 1.9 Ma →	N 22
Pliocene	LATE	TAIPIAN	*Gr. tosaensis*	← *Gr. tosaensis* FAD 3.1 Ma →	N 21
			Gs. fistulosus	← *Gs. fistulosus* FAD 3.2 Ma	N20
	EARLY	SAWAIAN	*Gr. margaritae*	← *Gs. nepenthes* LAD 3.9 Ma →	
			Sa. dehiscens	← *Sa. dehiscens* FAD 5.1 Ma →	N 19
			Gr. tumida tumida	← *Gr. tumida tumida* FAD 5.2 Ma →	N 18
Miocene	LATE	NEILLIAN	*Pu. primolis*	← *Gq. dehiscens* LAD 5.3 Ma ← *Pu. primolis* FAD 5.8 Ma →	N 17 B
			Gr. plesiotumida	← *C. nitida* FAD ← *Gr. plesiotumida* FAD 7.7 Ma →	N 17 A
			N. acostaensis	← *Gr. merotumida* FAD → ← *N. acostaensis* FAD 10.2 Ma →	N 16
	MIDDLE	HAVELOCKIAN	*Gr. menardii*	← *Gr. siakensis* LAD 10.4 Ma →	N 15
			Gr. siakensis	Gq. *nepenthes* FAD → ← *Fohsella lineage* LAD 11.5 Ma →	N 14 N 13
		ONGEIAN	*Gr. fohsi robusta*	← *Gr. fohsi robusta* FAD	N 12
			Gr. fohsi lobata	← *Gr. fohsi lobata* FAD 13.1 Ma	
			Gr. fohsi fohsi	← *Gr. fohsi fohsi* FAD 13.9 Ma →	
		INGLISIAN	*Gr. praefohsi*	← *Gr. menardi* FAD → ← *Gr. praefohsi* FAD 14.7 Ma →	N 11
			Gr. peripheroacuta	← *Gr. peripheroacuta* FAD 14.9 Ma →	N 10
			Gr. peripheroranda	← *Gt. insueta* LAD	N 9
			Pr. glomerosa	← *Orbulina suturalis* FAD 15.2 Ma	N 8
	EARLY	JARAWAIAN	*Gt. insueta*	← *Gs. sicanus* FAD → *Pr. glomerosa* FAD 16.3 Ma	N 7
			Cs. stainforthi	← *Gs. dissimilis* LAD 17.6 Ma →	N 6
		ANDAMANIAN	*Cs. dissimilis*	← *Gt. insueta* LAD 18.0 Ma →	N 5
			Gq. dehiscens	← *Gr. kugleri* LAD 21.8 Ma →	N 4B
LATE OLIGOCENE			*Gs. primordius*	← *Gq. dehiscens* FAD 23.2 Ma → ← *Gs. primordius* PAD 23.4 Ma →	N 4A
			Gr. kugleri		N 3

some land mammals and climate changes. Based on global climate changes, the 10 Ka period (that is 10,000 years) is taken as the upper boundary of the Pleistocene. In the European Standard Stratigraphic Scale, Pleistocene is marked at the commencement of the Calibrian marine stage and Upper Villafranchian non-marine stage in Italian sections. But in the Indian basins it cuts across hiatuses in some cases (Western and Indian shallow shelves) and some formations in others. This has been made mainly possible on the basis of faunal studies. In this case, the entry of *Globorotalia truncatulinoides* denotes the

boundary (Figure 10.6). Magnetostratigraphy, the study based on earth's polarity identification through ages, has also helped to arrive at more precise correlation and fixing of ages. Based on surface mapping, particularly in Uttar Pradesh and Assam, ^{14}C and thermoluminescence dating of samples collected (more from the Brahmaputra basin), a tentative attempt has been made to fix the boundary between Pleistocene and Holocene. This is located at a disconformity around a sediment dated 11,470±190 yrs. B.P. in Brahmaputra basin.

DISTRIBUTION

The geographical distribution, the nature of sediments and stratigraphic sequences in some parts of the country and their relevance to Quaternary tectonism, sea level and climatic changes are dealt with briefly here. Figure 10.7 broadly indicates the distribution of major Quaternary sediments in India.

Mainland Gujarat

Quaternary sediments in mainland Gujarat are of fluvial, aeolian and marine origin (Fig.10.8). A substantial part of the continental fluvial deposits owe their origin to changing fluvial system. Narmada, Mahi, Sabarmati and Luni rivers have had varied history of development/evolution, controlled by tectonics, climate and changes in sea level. Total exposed thickness of sediments in Narmada, Mahi and Sabarmati rivers is around 35 to 40 m, which date back to Late Pleistocene (~125 Ka). However the total continental Quaternary sediment thickness varies from 300-800 m in Mainland Gujarat. Invariably the base of the exposed sequences is made up of marine bluish clay, overlain by alluvial fan and alluvial plain sediments. Within the alluvial plain sediments, occur a 7-15 cm thick deeply pedogenised brownish red to reddish brown buried soil, which is laterally consistent and has been considered as a marker horizon for stratigraphic correlation. A series of alluvial fans were deposited along the Narmada-Son fault during Early Holocene. The Middle-Late Holocene sediments (~6 to 2 Ka) occur as valley fill terraces which are estuarine tidal in the lower reaches and fluvial in the upper reaches of the rivers of Mainland Gujarat. Along the coast are Middle to Late Holocene deposits comprising raised mud flats, stabilised (inland) coastal ridges and shelly beach rocks. The foraminiferal assemblage includes species of *Rotalia, Ammonia, Quinqueloculina, Spiroloculina, Triloculina, Elphidium, Nonionella, Nodosaria* etc. and constitutes the youngest marine sediments and these indicate shallow warm water conditions.

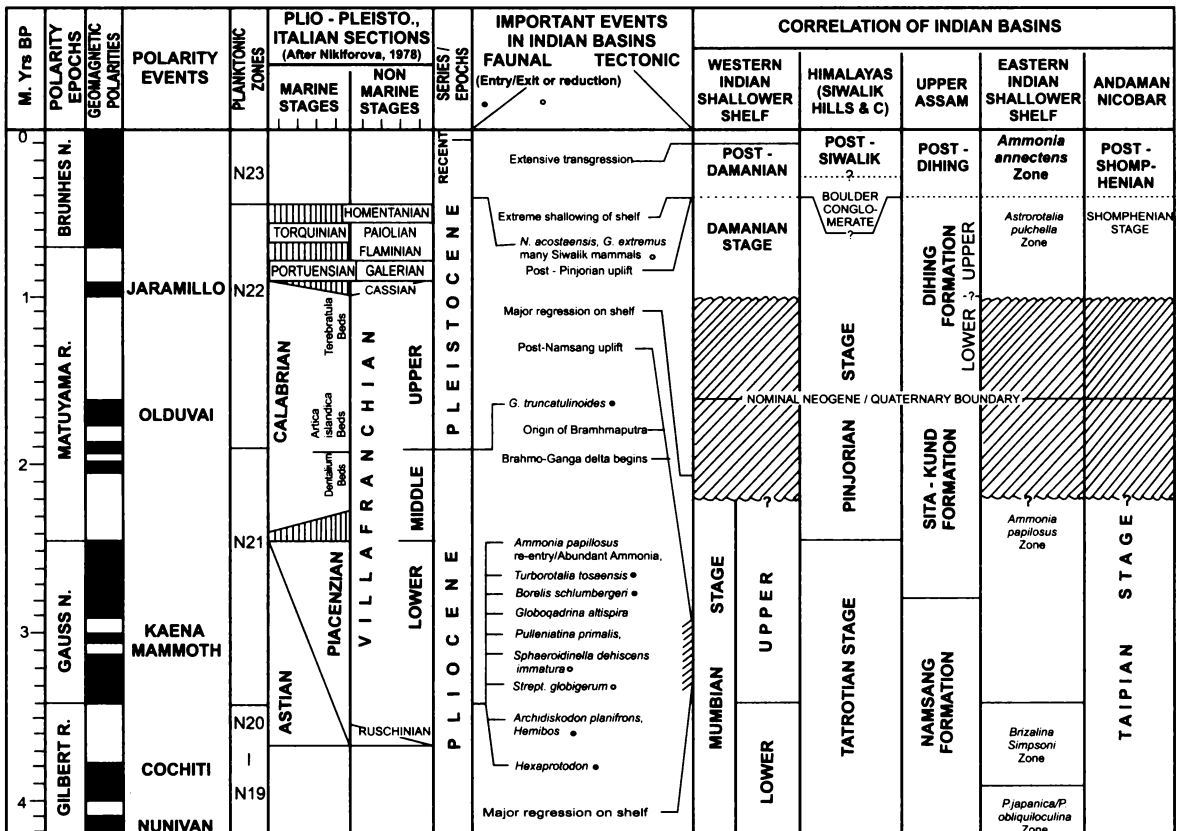


Fig.10.6. Neogene/Quaternary boundary in Indian basins (source: Ramanathan and Pandey, 1988). (Reprinted with permission from the Palaeontological Society of India).

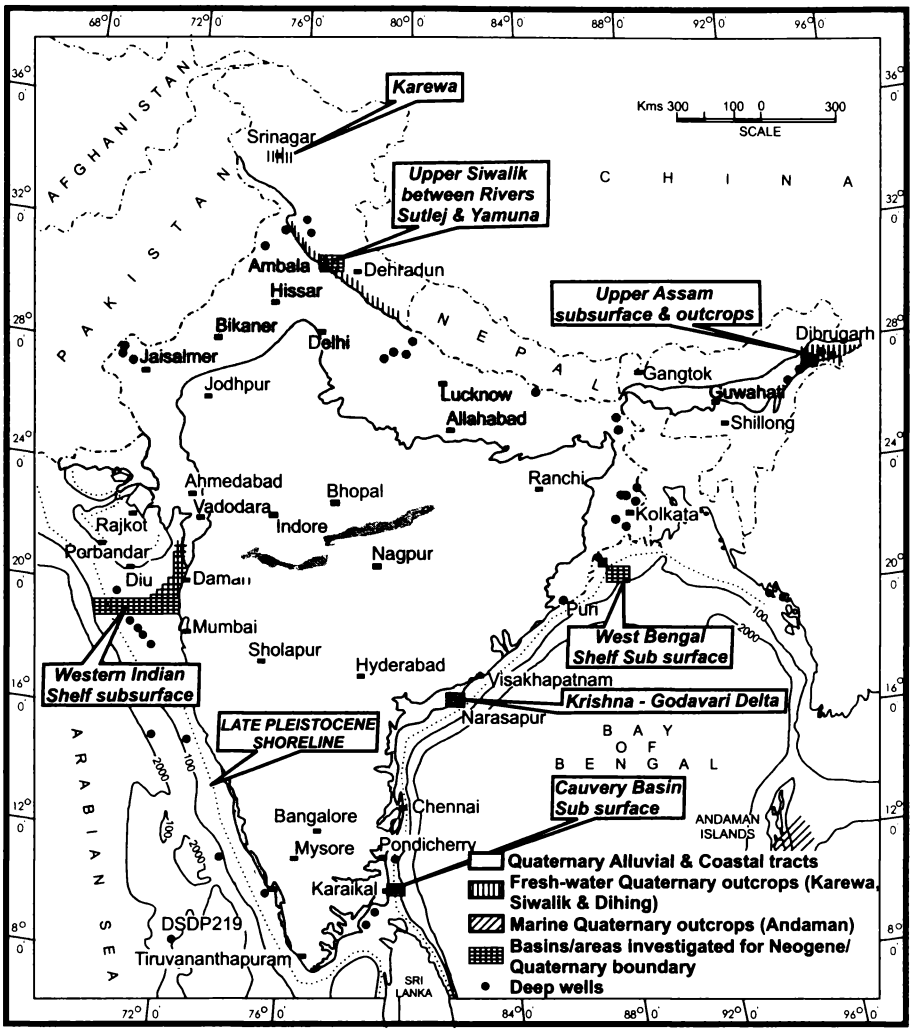


Fig.10.7. Quaternary sedimentaries of India (modified after Ramanathan and Pandey, 1988). (reprinted with permission from the Palaeontological Society of India).

The Cambay and the Narmada basins comprise a series of horsts and grabens supporting tectonic sub-basins that were subjected to periodic uplifts and subsidences relative to each other. This results in distinctive blocks of Quaternary sediments. The Late Quaternary tectonism is responsible for the present landscape of Gujarat.

Saurashtra

The Quaternary sediments of Saurashtra are of both marine and continental origin and the generalised stratigraphy is given in Table 10.15.

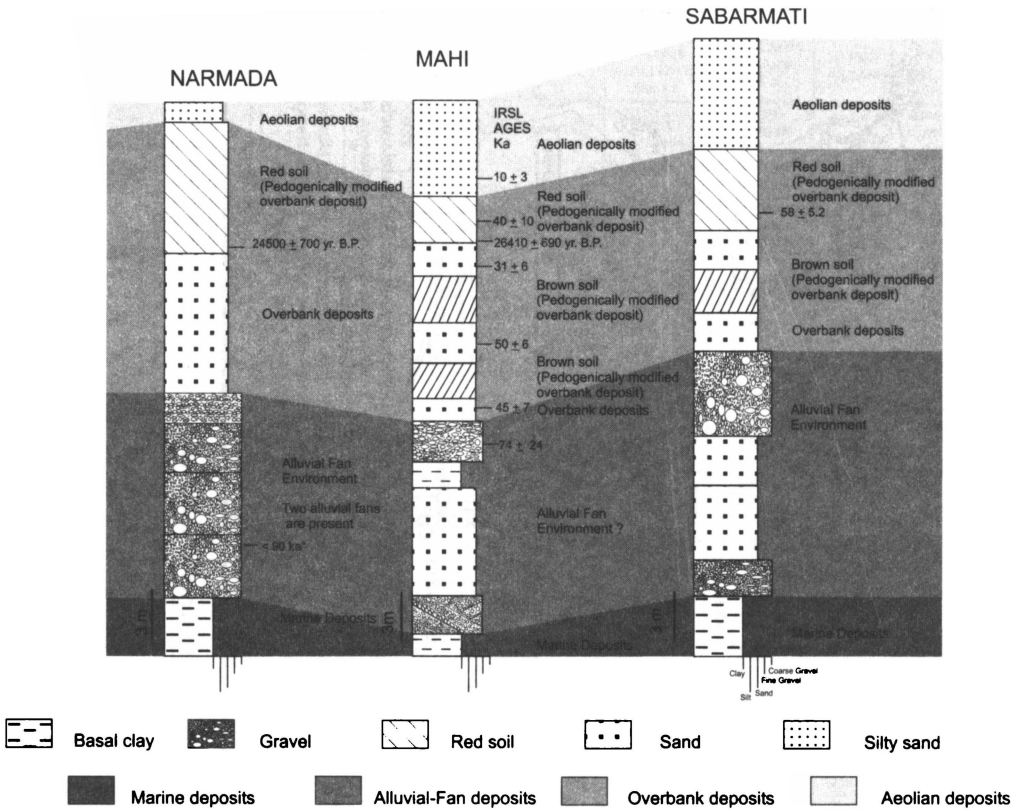


Fig.10.8. Physical stratigraphy of the exposed Late Pleistocene sediments (S1 and S2 surfaces) in the lower Narmada valley and the adjacent Mahi and Sabarmati valleys. Note the correlatability of the major aggradational phases. Dates are after Juyal et al. (2000), Tandon et al. (1997) and Allchin et al (1978) (source: Chamyal et al. 2002; © 2002, reprinted with permission from Elsevier).

Table 10.15. Stratigraphy of the Quaternary deposits of Saurashtra (after Merh and Chamyal, 1993)

Lithology	Thickness (m)	Age
Soil, alluvium, beach sands, tidal muds Beach rocks (Chaya Fm.)	- 2	Holocene
Miliolite Group: aeolinites Shell limestones	12 5	Upper to Middle Pleistocene
Gravel and sands	8	Lower Pleistocene
Basalts, laterites, Tertiary sediments etc.	-	Pre-Quaternary

Rocks of 'Miliolite Formation' referred to in literature as 'Miliolite' or 'Porbandar Stone,' are the most striking Pleistocene deposits of Saurashtra (Fig.10.9). These are "granular deposits composed of oolitic particles of calcareous sand and united together into a firm compact rock on the Arabian Sea coast having predominance of the form belonging to the genus Miliolina." Miliolidae on an average is about 2 to 5% of the total rock volume.

The miliolites occur all along the southern coast of Saurashtra from Gopinath in the east to Porbandar in the west. The highest miliolite occurrence is at Chota hill, which is about 165 km inland from the open sea. This hill is a 358 m high dome of Deccan Trap basalt. Outcrops of miliolites in the interior area occur along the gorges and slopes of hills of the Girnar ranges between Chotila and Rajkot and on the flanks of Chamardi hills of Sihor and of Osham hills.

Besides Miliolina the other foraminiferal forms found in the miliolites are – *Streblus beccari, Cibicides lobatulus, Elphidium* cf. *advena, Globigerina trilobata, G. bulloides, Quinquiloculina seminulum, Spiroloculina, Nonian scapha, Textularia* cf. *conica, Bolivina*, *Loxostromum* cf. *limbatum* etc. Ostracodes are also found associated with these assemblages. The forms are mainly of benthonic nature. Most of them are much rolled and difficult to identify and belong to Rotalidae, Elphididae, Nubeculariidae and Milioliidae families. Broken shell fragments of mollusca, bryozoa, echinoderm, ostracods, corals and algae are among the chief allochems.

Miliolites are assigned both marine and aeolian origin. The inland miliolites have a meteoric-vadose cementation of magnesian blocky spar. No feature of marine origin is indicated. They are of aeolian origin. In the coastal belt, however, marine macrofossils are found in the basal part of miliolite quarries. They are all well preserved and do not show any evidence of transport. Based on geomorphologic and pedologic criteria, the base of the 10-20 km wide miliolite belt may be of marine origin. The miliolite beds rest unconformably on the Pliocene strata, north of Porbandar. Summing up, the lower parts may

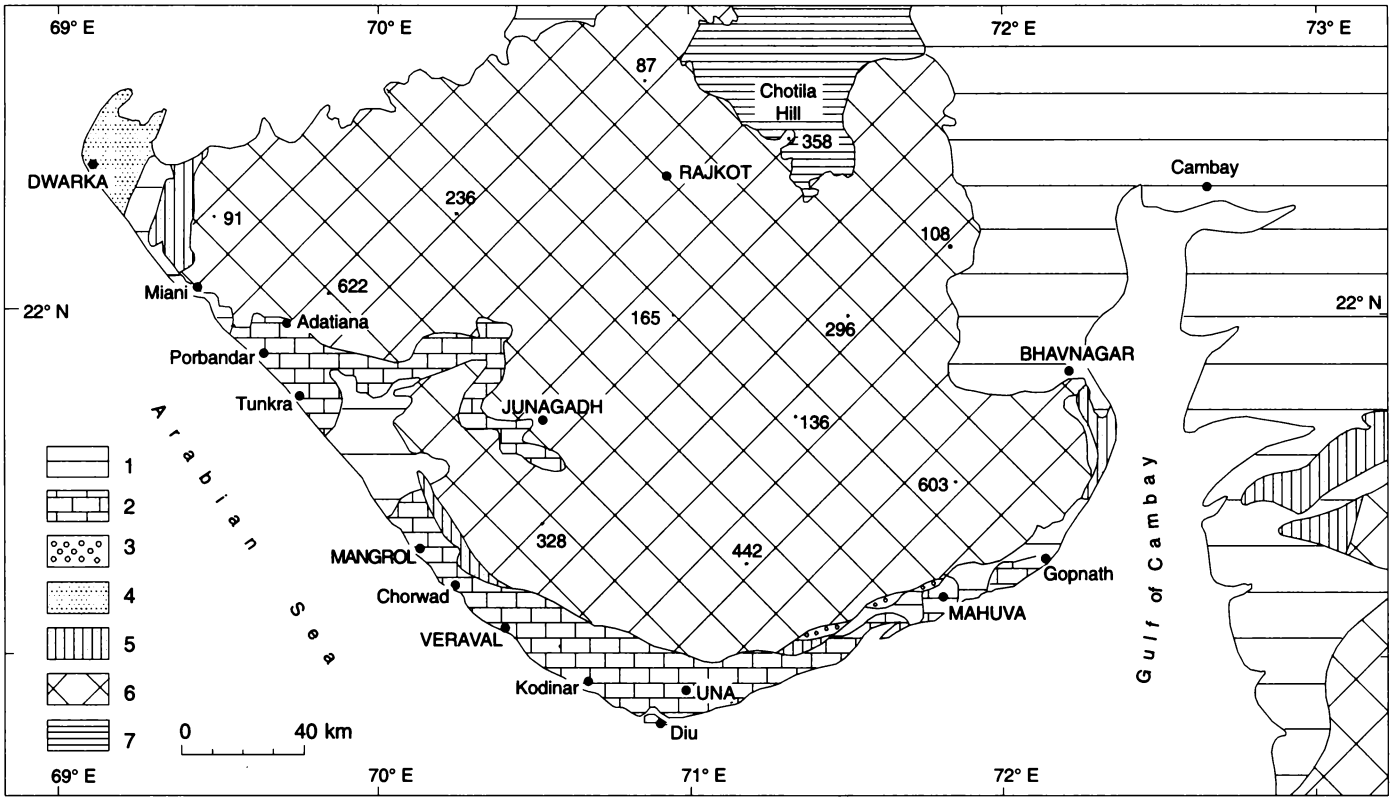


Fig.10.9. Geological map of the Saurashtra Peninsula: **1** - Holocene/Late Pleistocene, **2** - Miliolite Formation (Pleistocene), **3** - Laterite, **4** - Dwarka and Manchhar Formations (Neogene), **5** - Gaj Formation (Oligocene - Miocene) and Kirthar-Laki Formation (Eocene), **6** - Deccan Trap (Late Cretaceous - Eocene), **7** - Cretaceous (after Brückner et al. 1987, p.345)

be of marine lagoonal origin, whereas the upper parts of the beach ridges represent former coastal dunes. Fluctuations in sea level, and neotectonics have played some part, beside wind action, in the present day geographical distribution of these deposits.

The problem of dating the miliolites is complicated because of faunal components and the cementing calcium carbonate undergoing recrystallization during diagenesis. The ages in general are considered to be too young. However, different age ranges ($^{230}Th/^{234}U$ and ^{14}C) are noted from samples collected from different areas. For instance in Kutch, which is applicable to Saurashtra as well, three age groups were arrived at, spanning 50-70, 75-115 and >140 kyr ages. Ages above 200 kyr and around 30 kyr have also been obtained.

Holocene sediments of Saurashtra named Chaya Formation are made up of semi-consolidated to consolidated shell limestone (calc-rudites), coral reefs and oyster beds, mainly along the coast (Table 10.16). Recently miliolites have been recognised and mapped beneath the Chaya Formation along some parts of southeastern Saurashtra. The coral growth started in late Holocene and a few islands still support coralline forms. The fauna consists of lamellibranchs, gastropods, barnacles, corals, echinoderms and calcareous algae. These rocks seem to be the products of Holocene transgression. The sand of the present day beaches, alluvium of the rivers and the coastal plains constitute the youngest Holocene sediments. Radiometric dates available indicate only two age groups of corals in Saurashtra spanning 6000-7000 and 1,18,000-1,76,000 years.

Kutch

The Quaternary deposits of Kutch comprise the Rann sediments, alluvial fans, colluvial fans, fluvio-aeolian miliolites and silts along various rivers and

Table 10.16. Lithostratigraphy of the Quaternary deposits of Okhamandal (after Bhatt, 2000, p.141)

Stratigraphic unit Formation	Member	Lithology	Age
Holocene Deposits		Beach and dune sands, Tidal clays, Alluvium	Holocene
Chaya	Aramda Reef (4m)	Coral reef limestone	Late Pleistocene to Holocene
	Okha Shell Limestone (10 m)	Off white coloured bioclastic limestones and conglomerates	Middle to Late Pleistocene
~~ Dwaraka	Unconformity ~~~~	~~~~~~~~~~~~~~~~~~~~	Middle Miocene to Lower Pliocene

coastal deposits. The miliolite limestones occur as small outliers within the rocky area as obstacle dunes, sheet deposits and valley fill deposits. The alluvial deposits occur as cliffs along the various riverbanks. The Great Rann and the Little Rann represent filled up gulfs and mark the site of accumulation in a restricted marine environment. The Rann surface is salt encrusted and form salt lakes during rains. During the last 10,000 years, the area came under the influence of glacio-eustasy and seismicity-related tectonism, the two factors profoundly influencing the nature of sedimentation. The latest high magnitude event is the devastating earthquake of 26th January 2001 around Bhuj, with the epi-centre in the centre of Kutch.

Fossil avian eggshell fragments are described from the Kothara Formation of Pleistocene age, south of Naliya in Kutch district. This is the first record of avian eggshells from Western India.

CENTRAL INDIA

Quaternary deposits in Central India occur in two distinct depositional domains: (i) as thick tectonogenic and climatogenic sedimentary deposits in deep structural depositional basins of the Narmada and Purna-Tapi valleys and (ii) as thin conglomeratic fluvial deposits in shallow river basins of the Godavari, Wardha, Wainganga, Hasdo, Mahanadi, Son, Chambal and others.

Central Narmada valley, Purna valley and the Tapti (Tapi) valley are structural basins of Central India. Southern margin of the Central Narmada valley and the northern margins of the Purna and Tapti valleys are defined by two almost east-west trending regional faults, known as the North Satpura fault and South Satpura fault respectively. The reactivation along these faults during the Quaternary has given rise to accumulation of about 400 m thick Quaternary deposits in Narmada and Purna-Tapti Valleys.

Narmada North and Narmada South Faults bound the Narmada basin. At places the northern limit of the basin overlaps Narmada North Fault. The Quaternary fill rests over Deccan Trap, Gondwana sediments, and Precambrian Mahakoshal Group, Bijawar Group and granites. Neotectonism during the pre-Middle Pleistocene has resulted in the development of a deep basin with emergence of the Hoshangabad Plateau and Piparia Ridge, dividing the Narmada basin into three subdivisions (Fig.10.10).

All horizons from Lower Pleistocene to Holocene are met with in all the places, and a tentative attempt is made to arrive at an approximate correlation of the Quaternary formations of Central India with those in different river basins (Table 10.17). The interrelationship within a valley was worked out by superposition, soils, palaeosols, unconformities, overall lithology, volcanic ash and morphostratigraphy. The volcanic ash related to the younger Toba eruption

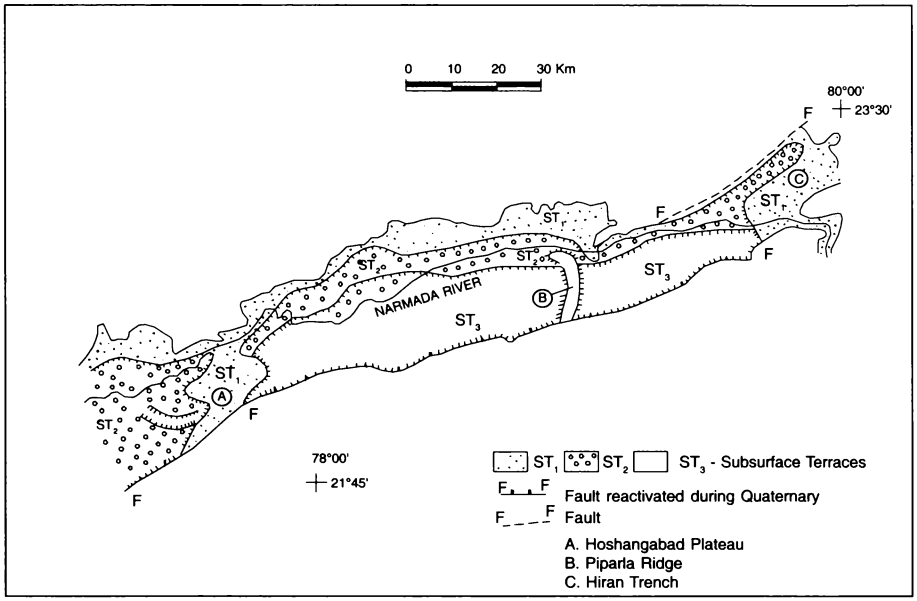


Fig.10.10. Map showing subsurface terraces (ST_1, ST_2 and ST_3) and structural framework of the Central Narmada Valley. ST_1 : Subsurface terrace with up to 50 m thick Quaternary cover; ST_2: Subsurface terrace with 50 m to 150 m thick Quaternary cover; ST_3: Deep Quaternary basins with up to 400 m thick sediments (after Tiwari, 1999, p.20).

forms a good marker horizon. The recognition of Toba ash bed as a marker horizon in the Quaternary sequence in different parts of the country is a significant contribution in the recent times. Extensive ash bed horizons recorded from the deep-sea cores of sediments in Bay of Bengal, have been correlated with the youngest Toba ash (YTA) of about 70,000 yrs. B.P.

The chalky white ash bed traced over a distance of 30 km from Ghogara to Khutali has a bedded appearance with parallel and at places cross lamination. It occurs as a persistent bed and varies in thickness from 0.50 to 1.5 m. It is unconsolidated, well-sorted, very fine-grained (< 0.20 mm), nonplastic and very light in weight (grain specific gravity 2.33). The occurrences are mostly along the lineaments trending NNE-SSW, which is known for repeated crust-mantle activity and very high heat flow. Both in Narmada and Son basins these are represented by silicic vitric ash. Chemical composition, mineralogy and shard morphology (with characteristic curved surface of fracture) of Son valley ash and Narmada valley ash compare well with the youngest Toba ash. Presence of Middle Palaeolithic flakes at the base and Upper Palaeolithic artefacts at the top of the Waghor Formation in the Son valley indicates that the associated ash is of Upper Pleistocene age.

Holocene sediments are essentially terrace deposits on either side of the rivers. Erosional terraces on hard rocks also exist. Figure 10.11 is a detailed

Table 10.17. Quaternary stratigraphic succession of Central India (after Tiwari et al. 2001, p.178)

Age	Formation	Lithology	Correlation
Holocene (15 m to 30 m of vertical dissection formation of inset terraces)	Ramnagar Formation Age: less than 4 ka	Gravel, sand, silt and clays of inset terraces	Khetaunhi Fm. of Son valley, Post black soil fm. of Western Maharashtra, Wardha fm., Wainganga fm., Dark grey silt fm.
Late Upper Pleistocene (Dissection and Aggradation)	Hirdepur Formation Age: 25 ka to 10 ka	Vertisol Structureless grey sandy silt Grey silt and fine sand Reworked Tephra Cross bedded sand, calc. sandstone conglomerate	Light grey silt formation of Tapti, Purna, Lower Godavari and Wainganga, Hasdo, Mahanadi valleys Siri fm. of Wardha, Waghor fm. of Son and Upper Bhima fm. of Western Maharashtra, Hirdepur fm. of Narmada valley
Early Upper Pleistocene (Dissection and Aggradation)	Baneta Formation Age: 118 ka to 75 ka	Brown soil Brown calc. silt, Volcanic ash, Brown calc.silt Dark carbonaceous clays Brown calc. silt Fine sand, Cross bedded sand Calc.sandstone, Conglomerate	Brown silt formation of Tapti, Purna, Wainganga, Lower Godavari, Hasdo, Mahanadi valleys, Jamalpur fm. of the Wardha valley, Patpara fm. of Son valley, Bori fm of Western Maharashtra. Baneta formation of the Narmada valley
Middle Pleistocene (Erosional Unconformity)	Surajkund Formation	Yellow clayey soil Steel grey and yellow clays Grey/Brown silts Fine sand, Cross bedded sand Gravels, Calc. Conglomerate	Sihawal formation of Son valley Surajkund formation of Narmada valley
Lower Pleistocene (Laterite and latosol formation)	Dhansi Formation	Red soil Red homogenous sand Yellow and orange sand Brown silt Grey sand and silt	Red silt formation of Purna valley Dhansi formation of Narmada valley
Lower Pleistocene	Pilikarar Formation	Laterite / latosol Gravels/Pediment cover deposits	Ferricreted pediment cover of Lower Godavari, Wainganga, Hasdo, Mahanadi and other smaller tributaries, Pilikarar formation of Narmada valley

geomorphological map of the Narmada-Tawa river confluence showing the disposition of different terraces and other features. Their relative elevations and mutual relationships can be gauged from the cross-sections provided. Narmada valley here shows development of three depositional terraces. The highest T_2 terrace represents the last alluvial aggradation during the Late Pleistocene. Subsequent dissection of T_2 terrace during Early Holocene gave rise to the lower T_1 terrace. Present flood plain forms T_0 terrace.

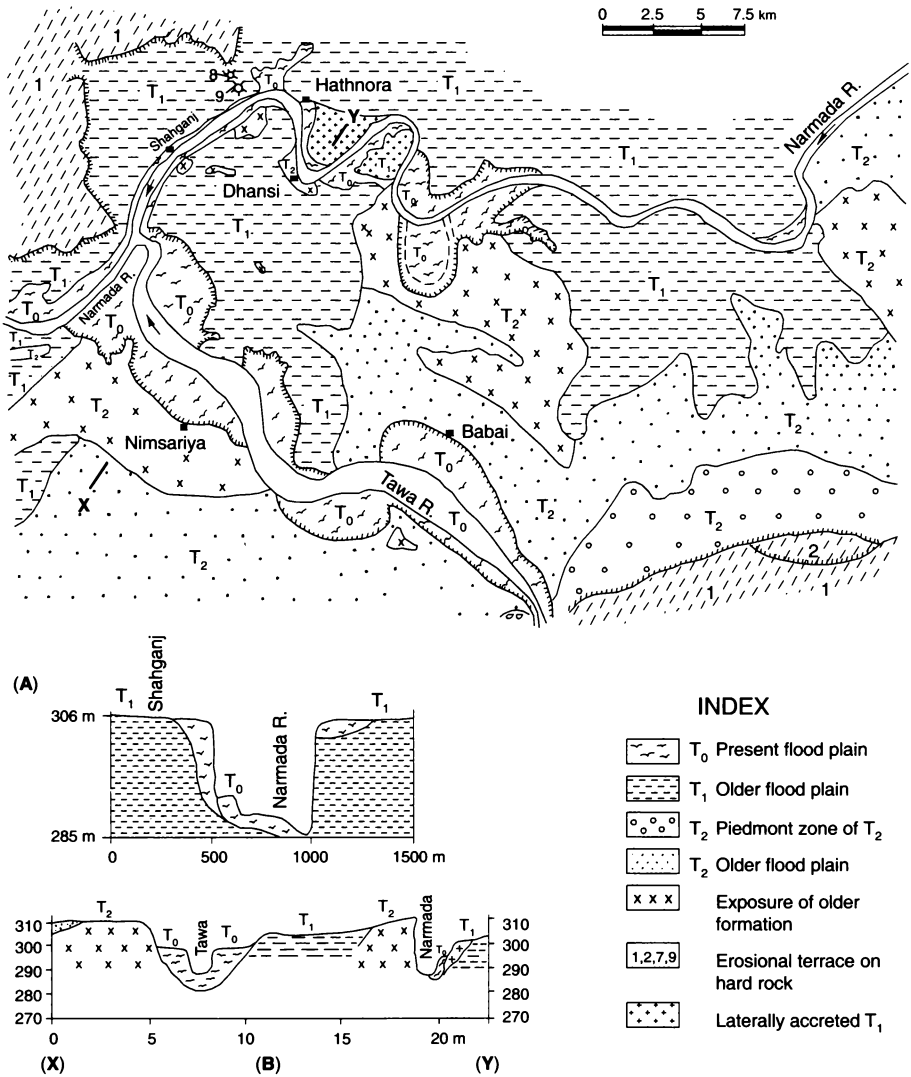


Fig.10.11. Detailed geomorphological map of the Narmada-Tawa river confluence area showing distribution of depositional terraces. **A.** Cross section of the Narmada river at Shahganj showing development of present flood plains at various levels related to low to overbank flood discharges. **B.** Cross section along X-Y showing disposition of depositional terraces. (after Tiwari and Bhai, 1997, p.15).

Table 10.18. Distribution of Fauna in Indian Pleistocene deposits and their probable ages (after Badam, 1988, p.282)

Locality	Important Fauna	Associated cultures	Probable age		Environment
Kurnool, Ghod, Manjra, Pravara, Godavari	*Canis sp., Bubalus* spp. *Cervus spp. Bos namadicus Elephas hysudncus, Elephas maximus, Rhinoceros unicornis Bos indicus, Hexaprotodon Palaeindicus*	Bone tools, Burins, blades, points Scrapers, Flakes, Blades, Points, Borers	Upper Palaeolithic Late Middle Palaeolithic	Late upper Pleistocene (also dated by C^{14}) 40,000-15,000 BP	Savannah type with pockets of forests and swamps (humid in Kurnool)
Central Narmada (Upper group) Palmar	*Equus namadicus, Bos namadicus, Hexaprotodon, palaeindicus, Elephas hysudricus, Stegodon insignis-ganesa Cervus* sp.	Scrapers, Flakes Flake-blades, Pionts, Borers, Handaxes, Cleavers, Polyhedrals Discoids, Choppers	Middle Palaeolithic (Late-Acheulian)	Early Upper Pleistocene	Savannah grassland interspersed with swamps
Central Narmada (Lower group)	*Sus namadicus, Elephas hysudricus, Equus namadicus Bos namadicus, Hexaprotodon namadicus, Stegodon insignis-ganesa*	Choppers, Handaxes, Flakes	Palaeolithic (Lower Acheulian)	Middle Pleistocene (not well established)	Savannah grassland interspersed with swamps
Lower Karewa, Pinjor of Upper Siwaliks	*Equus sivalensis, Rhinoceros sivalensis, Rhinoceros palae-indicus, Elephas hysudricus Bos* sp., *Archidisckondon planifrons, Sivatherium giganteum*	No stone age tools		Lower Pleistocene	Valley and open savannah grassland with swamps

Life: Fauna and Primate: The preliminary taphonomical studies (dealing with the burial of the animal) carried out on an assemblage from the Central Narmada Valley, Madhya Pradesh reveals that the assemblage had undergone hydrodynamic sorting resulting from the transportation of the fossils. Also there has been a delayed burial of the bones. Field sedimentalogical evidence supports the occurrence of the assemblage in channel deposits under the influence of moderate currents.

Pleistocene deposits of Central Narmada Valley (Table 10.18) yielded a partial hominid skull and an array of Stone Age implements, along with a diverse microvertebrate assemblage (micro mammals, fish, amphibians, reptiles).

The fossilized skull of Narmada *Homo erectus* was found first by Sonakia (1984), embedded in a conglomerate bed in the Narmada valley of India. This bed occurs at the basal part of a formation sandwiched between two other formations of 73,000 and 74,000 yrs B.P. The conglomerate bed has also preserved fossils of *Hippopotamus namadicus, Equus namadicus, Stegodon namadicus, Sus namadicus* etc. having Middle Pleistocene affinity. All these stratigraphic and palaeontological evidences point to a Middle Pleistocene age for the Narmada *Homo erectus.*

Fluorine analysis of bones and fossils from Quaternary deposits has been recently attempted. From the site Hathnora in the Central Narmada Valley, the *Homo erectus* cranial fossil gives an F/P ratio of 7.53, and based on this, as well as morphology and the associated cultural material, it can be dated to the late Middle Pleistocene.

Synthesis of palaeomagnetic and palaeontologic data in Central India leads to the inference that all the sequences showing Normal polarity are to be grouped in the Brunhes Normal polarity and reverse polarity sediments in the Matuyama © polarity epochs. Based on the polarity record, the Dhansi Formation (*see* Table 10.17) is estimated to be more than 0.73 Ma and others as younger. The study establishes that the Quaternary sedimentation record in the Narmada valley extends to the Lower Pleistocene. Tephra beds from Narmada and Kukdi valleys namely, the Pawla and Gurwara in Narmada, and Bori in Kukdi valley, show Normal magnetic polarities. These are grouped in Brunhes Normal polarity, are younger and estimated to be 0.5 Ma. It is obvious that good correlation of sequences in the Narmada valley can be best established with the aid of vertebrate fossils and archaeological material.

Tables 10.19 and 10.20 give the latest data on the chronological sequence of fossils in the Narmada valley and also the related litho- and biostratigraphy.

Rajasthan

The Quaternary deposits in Rajasthan are essentially of fluvial, lacustrine

Table 10.19. Chronological sequence of fossils in Narmada Valley (after Badam, 2001, p.ixx)

Upper Pleistocene to Holocene	*Antilope cervicapra, Cervus unicolor, Cervus duvauceli, Axis axis, Boselephas ragocamelus, Equus asimus, Elephas maximus*
Upper Pleistocene*	*Sus palaeindicus, Hexaprotodon palaeindicus*
Middle Pleistocene*	*Elephas namadicus, Sus namadicus, Hexaprotodon namadicus*
Middle to Upper Pleistocene	*Elephas namadicus, Sus namadicus, Equus namadicus, Bos namadicus*
Lower to Upper Pleistocene	*Elephas hysudricus, Stegodon insignis ganesa*

Note: The above biochronological sequence is based on recent data from Belan and Narmada valleys of Western Maharashtra including Godavari, Manjra, Krishna, Ghod etc.
* Index fossils

Table 10.20. The litho- and biostratigraphy of the Narmada Valley based on recent data (after Badam, 2001, p.ixx)

Approximate Age	Lithological units	Approx. thickness (in mm)	Palaeontological and Archaeological materials
Early-Mid Holocene (10,000 to 4,000 BP)	Dark brown moderately consolidated silt and gravel	-	Semi mineralised bones Mesolithic
Terminal Pleistocene (15,000 to 10,000 BP)		-	Upper Palaeolithic tools
Late Upper Pleistocene (40,000 to 15,000 BP)	Reddish clay band Yellowish brown calcreted sands and gravels	10-13	Middle Palaeolithic tools and Upper Pleistocene fauna
Late Middle Pleistocene to early Upper Pleistocene (150,000 to 40,000 BP)	Reddish brown calcareous silt and well cemented boulder gravels	3-8 (15 m at Hathnora)	Early Palaeolithic and Middle Palaeolithic tools and Middle to Late Pleistocene fauna, *Homoerectus narmadiensis** and Late Acheulian artifacts

* The date of the hominid fossil is now estimated to be in the range of 150,000-200,00 B.P.

and aeolian origin. The onset of Quaternary marked a major transformation in climate from humid, tropical to arid, desertic conditions, which continued with periods of comparative wetter and drier phases. Based on the nature of sediments, associated landforms and mutual relationships among them in about four areas, namely Kantli-Ghaggar basin, Luni Basin, Sambhar Lake and Jaipur

areas, the following tentative informal nomenclature is suggested for the Quaternary formations of Rajasthan:

(F: fluvial; A: aeolian; L: lacustrine).

Luni Formation - F, A, L; lacks soil development
Jaipur Formation - only F
Sambhar Formation - F, A, L; grey loamy soil
Churu Formation - F, A, L
Bikaner Formation - F, A, L; latosols, calcrete, evaporites
~~~~~~~~~~~~~~Unconformity ~~~~~~~~~~~~~~~~~~~~
Malani, Palaeozoic, Mesozoic; Tertiary Calcretes and Ferricretes

Studies on alluvial and aeolian sequences along the river Luni in Barmer district of Quaternary age have thrown light on the palaeoenvironment and palaeoclimate of the region. A luminescence chronology attempted gives dates ranging from about 250 Ka to about 5 Ka (Table 10.21). The lithology indicates varying facies. Associated with the sediments are human implements.

The occurrence of surface and near surface calcretes and gypsum crusts, in the Chichru-Bikaner area in subsurface sequences of fluvio-aeolian sediments indicates climatic vicissitudes in the Late Quaternary from humid to arid and vice-versa.

In addition to the glacial deposits of Permo-carboniferous, known as Bap Boulder Beds that are overlain by fossiliferous Badhaura Formation of Permian age, a spread of pebbles, cobbles, boulders and erratics, has been erroneously named as "Bap Boulder Spread" or "Glacial Pebble Spread". The spread comprises loose rock fragments scattered over the surface without any matrix. It not only overlies the Nagaur Group of Cambrian age, but also transgresses over the Badhuara Formation of Permo-carboniferous age, the Lathi Formation of Jurassic age, Palana and Marh Formations of Paleocene age and Jogira Formation of Eocene age. The rock spread is seen near Nagaur and northeast of Nagaur, around the villages of Bhojasar-Jasurana and Hamira in the eastern part of Jaisalmer district. Such pebble spread has also been observed on hill slopes between Jaisalmer and Damodara. The erratic boulders mainly of quartzite are also seen near Kanod and the Te-Tekkar-plateau. Although without any incontrovertible evidence of glacial origin, the spread is regarded possibly of glacial origin and of Pleistocene age.

Many of the lakes in Rajasthan contain a thick Quaternary sedimentary pile (Fig.10.12). The basement for the lake sequence at Sambhar is marked by the Precambrian rocks. In this sequence five fluvial, two aeolian and four lacustrine sedimentary facies can be distinguished. The Ghaggar basin, bounded by faults, contains more than 350 m thick sediments. Quaternary fluvial, fluvio-lacustrine deposits constitute the bulk of sediments. Poheda, Kanod, Dedia,
~~~~~~~~~~~~~~

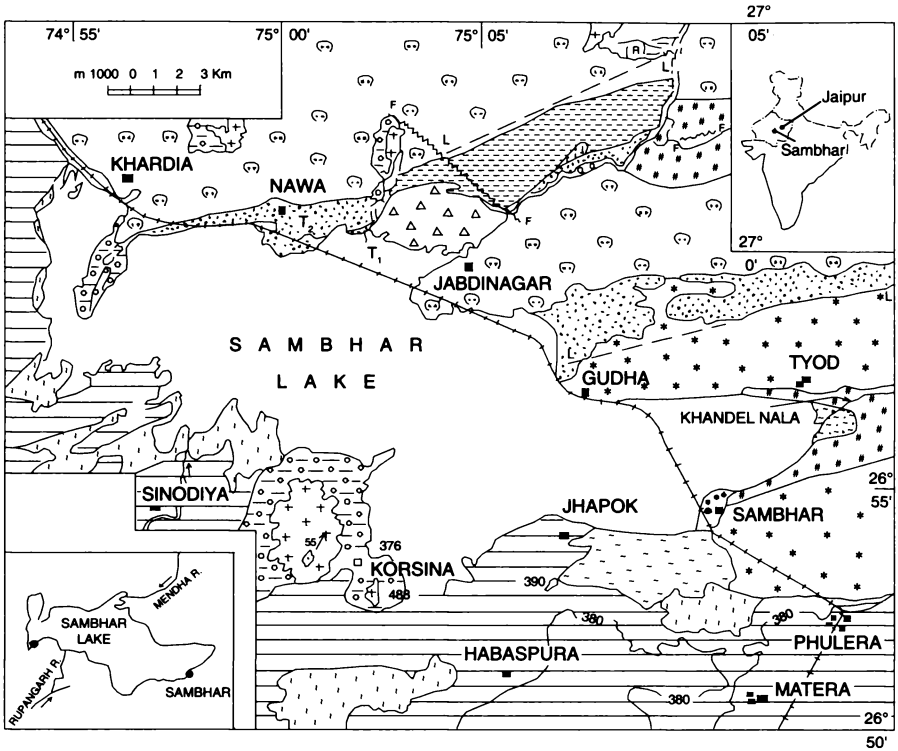
Table 10.21. Summary of major lithofacies characteristics, archaeo-stratigraphy and luminescence dates of Quaternary alluvial sequences. Luni basin 'L' represents age based on luminescence dating. 'A' represents speculated age based on the presence of archeological evidences. 'P' stands for pottery (after Jain et al. 1999, p.292)

Age	Type	Lithology/Major facies	Archaeo-stratigraphy	Age
HOLOCENE		Silts/silty fine-sands (pottery)	Recent	Recent (P)
	Type III sequence near Karna	Pottery bearing pebbly gritty very coarse sands (pottery, animal bones, gastropods)	Chalcolithic	~5 ka (P)
	Type III: Kundala/ Karna/Bhuka 1 (eastern bank)	Dunal sand cover (medium to fine sands)	Microliths on top of some sand dunes	Older than ~5 ka (A)
EARLY TO MIDDLE LATE PLEISTOCENE		Well sorted medium to fine sands/sand-silt alternation		95±28 ka (L)
	Type II sequence in Karna/Khudala sections	Planar cross bedded pebbly gritty coarse sandstone (implementiferous in Karna sequence)	Middle Paleolithic	72±15 ka (L,A)
EARLY TO MIDDLE PLEISTOCENE		Upper heterolithic facies		45±11 ka ?(L)
		Medium scale cross bedded pebbly gritty coarse sandstone		324±103 ka (L)
	Type I Sindari/ Bhuka sequence	Lower heterolithic facies		98±29 ka ?(L)
		Large-scale planar cross-bedded pebbly gritty coarse sandstone		208±50 ka (L)

Bap-Malar, Pachpadra, Thob, Talchhapar, Lunkaransar and Didwana are the saline lakes in the desert, except for Sambhar and Pushrik, which are within the Aravalli Mountain ranges.

Occupying a substantial part of Western Rajasthan, three distinct generations of aeolian deposits have been recognised in the Thar desert – (i) youngest active aeolian dunes, (ii) semi-stable pedogenised dunes of post-Kalibangan cultural period (300 to 2000 years B.P.) and (iii) consolidated older aeolian deposits (~14 Ka B.P.). Further from the subsurface column, aeolian sedimentation has been recognised, which suggests phases of aridity during the Middle Pleistocene. The general lithostratigraphy of the Thar Desert is given in Table 10.22.

The dune sands were largely derived from the alluvium, although foraminifera in the sands indicate a contribution from the Arabian Sea. From the orientation of the dunes it can be easily inferred that their movement is guided by the southwest summer monsoon. Based on data from archaeological



LEGEND

Landforms / Lithology

- Barchans / obstacle dunes; white yellowish brown
- River (flood plain) / Channel bar / Deltaic plain / Present saliferous playa/ lake, Coarse fine sand to clay, saliferous
- T_1 Terrace / Palaeo-shore, saliferous, grey silty clay
- T_2 Terrace / Palaeochannel / Colluvial fans, grits, coarse to fine sand to clay with brown soil
- Sandsheet / undulatory sand mounds / longitudinal dunes, yellow with brown, fine sand with specks of kankar
- Older palaeochannel/palaeo-lake grit to sand to clay sediments with calcareous duricrust
- Pediment, laterocalcretes (massive nodular vermicular) with/without sandcover
- Hill / Ridge / Residual hills, quartzites interbedded with phyllites and schists
- Lineaments / Faults
- Drainage reversal / aeromagnetic breaks
- Contact / contours

Fig.10.12. Quaternary geological map of Sambhar lake, Rajasthan (after Sundaram et al. 1996, p.207).

Table 10.22. General Quaternary lithostratigraphy of the Thar desert (after Dhir et al. 1988) (source: Sinha-Roy et al. 1998, p.230)

	Southwestern Sector	Eastern Sector	Northeastern Sector
Quaternary	Non-calcareous, loose fine sand and admixed alluvium/colluvium	Well sorted, fine to very fine loose sand	Gravel, pebbles and boulderswith coarse calcareous polymict conglomerate
	Calcareous sand and silt, weakly developed kankar pan	Calcareous and silty clays	Calcareous silty sand and clay with gastropods, alternate sand, black silt/ clay layer with isolated halite beds
	Calcareous/non-calcareous fine sand with kankar, cross-bedding and bio-turbation structures	Well-sorted, fine semi-consolidated sand	Oxidised well-sorted fine sand with pedo-calcic horizon
	Coarse sand sheet-flow and run-off deposit, kankar pan, calcareous/ non-calcareous fine sands, silt, rolled kankar clasts	Calcareous sand and silt, hard kankar disseminations and pans	Coarse sand with calcareous horizon
			Silty sand and clay with kankar pan, moderately oxidised well-sorted sand with pedo-calcic horizon
	Calcareous sand/well sorted, massive with lumpy indurated calcrete	Lacustrine white and grey marl, sand calcareous clays with gastropods, ostracods and forams	Sand with silt and clay, unoxidised consolidated aeolian sand
	Marly clays, calcareous sand and silt	Well sorted pedo-calcified sand with clay and silt	Coarse to fine sand with silt
	Well sorted consolidated calc-cemented sands, impersistent calcareous concretions, coarse sub-angular fluvial sand	Consolidated sand and silt pedocalcified mottled clay and sand	
	Calcretised gritty conglomerate, coarse sand with lateral and vertical variation to mottled finer sand and clay	Calcretised gravel, gritty sandstone and ferruginous clays, boulder conglomerates ferricreted gravel with clay	
	- - - -Unconformity - - - -	- - - -Unconformity - - - -	- - - - Unconformity - - - -
Tertiary-Cambrian		Lignite bearing clays and sandstone	
Pre-Cambrian	Malani rhyolites and Jodhpur Sandstone	Nagaur Group Delhi Supergroup	Delhi Supergroup

findings, radiocarbon and thermoluminescence dating, it is inferred that the dunes were accumulating from at least 20,000 yrs B.P. and were stable by the middle to late Holocene. It may be noted that the mobility of dunes continued in the Holocene as well unlike in the other middle latitude dune fields. A rate of vertical sand accumulation of 2 cm per year and horizontal movement of 9 cm per year has been estimated. Dune building in Thar during the past 70,000 years has been found to be episodic such that aeolian units are seen interrupted by evidences of less arid phases. That there was stability for a while is indicated by the presence of layers of pedogenic carbonates. Aeolian accumulation and human occupation have occurred at least since the Lower Palaeolithic times as inferred from implements associated with periods of sand accretion.

Many physiographic depressions with salt beds (ranns or playas) with roughly elliptical shape occur in the desert. These are inferred to have formed due to deflation in the wind shadow zone of a hill and stream trapping by longitudinal dunes. There are many longitudinal, transverse, parabolic and obstacle dunes, besides barchans (Fig.10.13). Some of the dunes are highly dissected by rills and gullies and have coarser sheet-wash deposits within their profile.

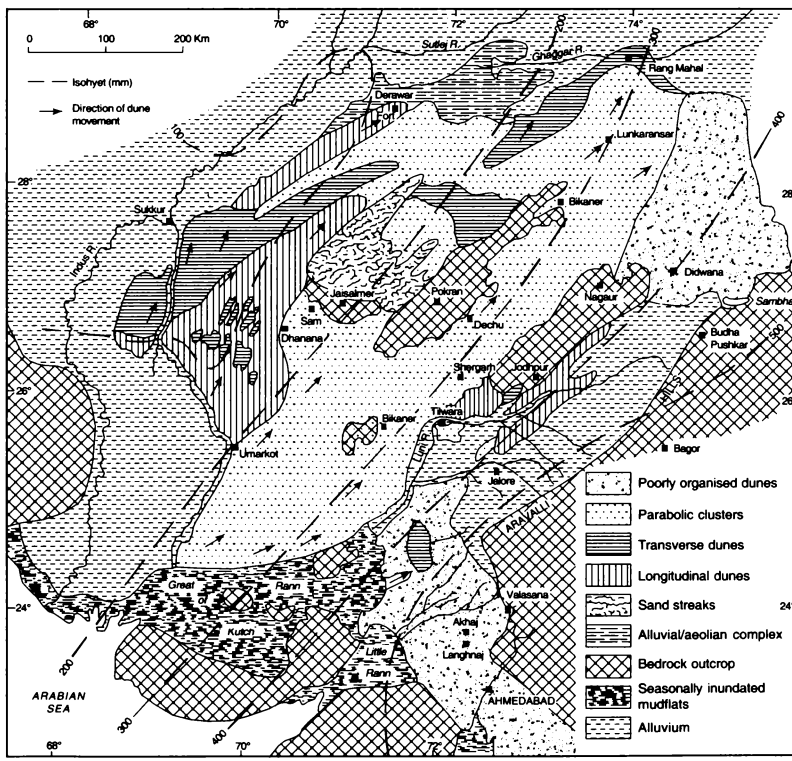


Fig.10.13. Thar dunefield showing dune types and their locations (after Wasson et al. 1983, p.119; reprinted with permission from Gebr. Borntraeger Verlagshuchhandlung; http://www/borntraeger.cramer.de)

The overall climatic history of Quaternary as inferred from the lacustrine sedimentation and archaeological evidences can be summarized as below:

3.5 Ka to Present	-	Warm dry with frequent draughts and seasonal extremes
4.5 to 3.5 Ka	-	Warm humid with less extremes of climate
10 to 4.5 Ka	-	Warm humid with frequent floods
Before 10 Ka	-	Cold and dry
Last Glacial Maximum (18,000 yrs. B.P.)	-	Extreme cold with hypersaline conditions

Amongst the various types, hard nodular calcrete is the most extensive and is found in the Pleistocene aggraded alluvial plains, buried pediments, piedmonts and to some extent also in the latest Pleistocene aeolian sandy plains and inter dunes. Well-developed nodular calcrete is also seen within and below the Late Tertiary ferricretes around Jaisalmer (*see* Table 10.22). It would seem that calcrete formation has taken place in arid-semiarid environments during the major part of Pleistocene. A form of calcrete, called *kankar*, is widely reported from the soils in Indo-Gangetic alluvial plains. There are pedogenic, vadose, phreatic and hydromorphic calcretes. They are common in Rajasthan and Gujarat in Late Pleistocene and Holocene.

Jammu and Kashmir

With a break in deposition during Pliocene times, the Pleistocene deposition took place in the Kashmir valley in the form of fluvial, lacustrine and aeolian deposits known as the Karewa deposits and in Ladakh in the form of Pleistocene terraces and horizontally disposed gravel and clay beds. In the Zanskar area, in the Padam and the Ligti valleys, the Quaternary deposits are made up of old moraines and erratics, river terraces, new moraines and hill washes.

The Kashmir valley is bowl-shaped, rather flat intermontane valley, about 140 km long, and at its maximum 40 km wide. The Karewa basin (Kashmir valley) is surrounded by mountains on all sides. The Great Himalayan Range and Saribal Range constitute the northeast flank, while the Kazinag Range and Pir Panjal Range constitute the southwest flank. The southwest flank of the valley has risen more than the northeast flank both during and also after the deposition of the Karewa sediments. Some small patches of the Karewa sediments have been raised to considerable heights in the Pir Panjal Range, and these are referred to as Margs.

Lydekkar, in the late nineteenth century, and about half a century later De Terra and Paterson were the earliest to study the Karewa sediments. Initially

the thick conglomerate horizons were mistaken for glacial deposits. However, later studies established their affinity to tectonically generated fluvial sequences. The Karewa sedimentary sequence is related to a vast fluvio-lacustrine basin spread over the entire Kashmir valley floor. There are a few loessic strata, particularly at the top with flood plain like deposits.

The Karewa deposits of fluvial, lacustrine and aeolian origins were deposited initially in a large lake, which once covered the whole of Kashmir valley floor. The Karewa Group includes the entire succession of the sedimentary cover of Pliocene to Holocene age, lying with profound unconformity over the Precambrian to Mesozoic rocks. The total thickness of the Karewa succession is about 1300 m. The Table 10.23 gives the scheme of subdivision of the Karewa sequence.

Table 10.23. Scheme of sub-division of the Karewa sequence (after Bhatt, 1989, p.9)

AGE		LITHO-STRATIGRAPHY	KASHMIR VALLEY	
			SOUTHWESTERN PART	NORTHEASTERN PART
RECENT		ALLUVIUM	ALLUVIUM	
PLEISTOCENE	Up.	DILPUR FORMATION	DILPUR FORMATION	
	Md.	NAGUM FORMATION	Shuplyan Member / Angular unconformity	Pampur Member / Disconformity; Krungus Member
	Lr.	KAREWA GROUP	Methawoin Member	
PLIOCENE	Up.	HIRPUR FORMATION	Rembiara Member	Sporadically exposed
	Lr.		Dubjan Member	
		PRE-KAREWA	MOSTLY PALAEOZOIC AND TRIASSIC BASEMENT	

The lower two formations, Hirpur and Nagum, are separated by an angular unconformity in some parts of the basin and elsewhere they have only a disconformable to gradational contact. However, the contact between the Nagum Formation and uppermost Dilpur Formation is conformable everywhere (Table 10.23). Figure 10.14 presents the lithostratigraphic map of the Karewa Group in the Kashmir valley. The main lithological constituents of the Karewa are plastic, grey to bluish grey, light grey sandy clay, fine to coarse, green to purple sand, conglomerate, lignite and lignite clay in the lower part (i.e. Hirpur Fm.). Fine to coarse greenish to purplish and grey and ochre sandy clay, ochre and cream coloured marl and gravel occur in the middle part (i.e. Nagum

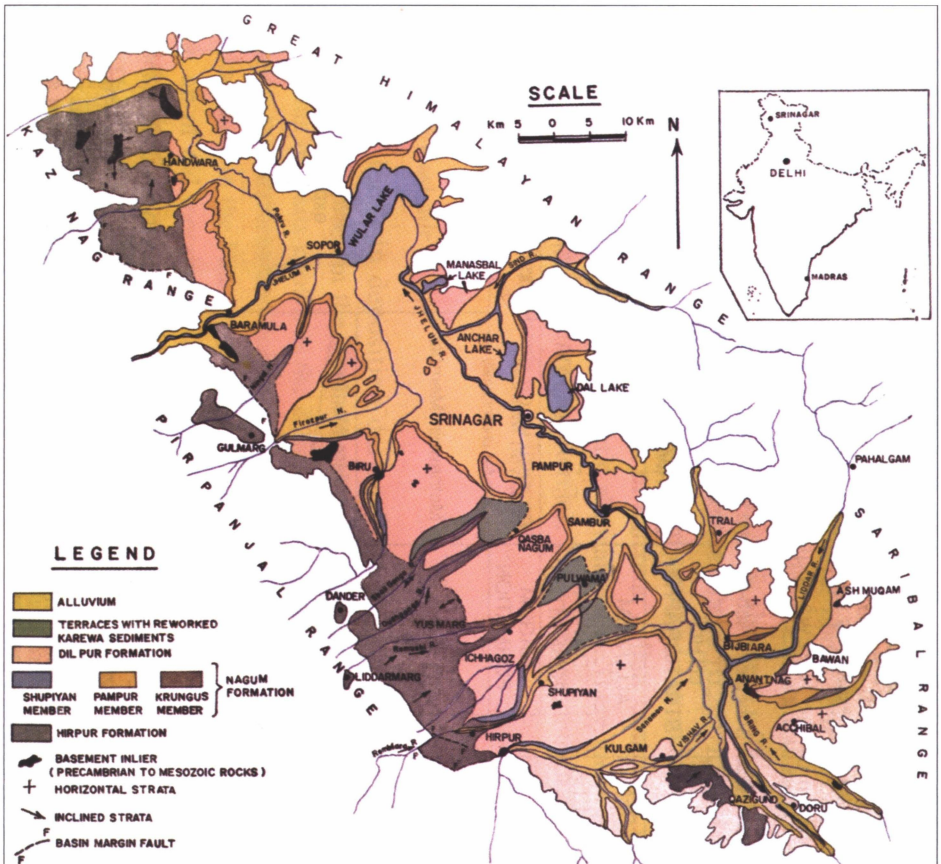


Fig.10.14. Lithostratigraphic map of Karewa Group, Kashmir valley, Jammu and Kashmir (after Bhatt, 1989)

Formation). The loam sediment of Dilpur Formation represents deposition after the obliteration of the major lake system and represents a long time span from the Middle Pleistocene to the Holocene. The lake was mostly 5-10 m deep, with a few parts reaching depths of ca.30 m (Hirpur lake) fed by rivers from adjacent mountainous areas. There were marginal swamps where lignite sediments developed. At the end of Hirpur phase of sedimentation the Karewa lake gradually started receding from the southwest side of the valley toward the centre, in more than one pulsation. The filling up of the lake led to the obliteration of a major lake system and the uplift of the Kashmir valley floor.

The flora and fauna of Karewa sediments show mixing of communities of different climatic zones and ecological niches, because of the geomorphic situation of the basin. The micromammal assemblage is represented by murid rodents, microtine and soricid insectivores of Lower Pleistocene age. A change in climate took place because of the uplift of the Pir Panjal Range, which in turn led to shifting of vegetational zones towards lower altitudes and southward migration of monsoon forests. Plants, which are now living at a height of 1500 m, are found as fossils at about 3200 m.

There have been many conflicting views regarding the age of the Karewa sediments. However, based on some radiometric dating, they are considered to extend from Pliocene to Upper Pleistocene. Thermoluminescence dating of the Dilpur sediments in the Korapur section gave an age of 130 Ka at 12 m below the top surface, while the total sequence is about 24 m thick. This suggests that the loess sequence in Kashmir probably goes back to at least 300 Ka. Loess started depositing in the Kashmir basin after the marker gravel bed was laid. The Karewa unconformity has been dated to c.350,000 yrs. B.P. Loess in Kashmir therefore post-dates this event. Since it forms top of the Karewa or Udra, the deposition may have stopped with the end of Pleistocene, though it is considered to have started around 200,000 yrs. B.P. and Jhelum river emerged around 85,000 yrs. B.P. draining out the Karewa lake. The spatial and temporal variation of Kashmir loess deposits has been explained as the function of palaeotopographical configuration consequent to the Pir Panjal Range uplift (1700-3000 m) datable at 0.4 Ma. Loess palaeosol sequences overlying the Karewa sediments of the Kashmir basin are up to 25 m thick and contain many Middle and Late Pleistocene palaeosols. Four to five interglacial palaeosols can be detected in the loess sequences; therefore the lowest palaeosol must be at least 350 Ka old.

Holocene deposits in Kashmir include alluvial tracts, flood plains, river terraces, talus, scree, fans, Harwan cave deposits, travertine etc. Recent alluvium and scree cover a large area in the Upper Indus, Shyok and Zanskar valleys. Widespread gently sloping talus fans and wind blown sand characterising the arid climate in the area occupy long stretches of the valleys.

Himachal Pradesh

Quaternary deposits in Himachal Himalaya fall into two major categories: (i) Intra-montane basin fills occurring in various tectonic zones, and valley fill sequences of limited width along with the linear extent of major Himalayan drainage and (ii) submontane basinal fills in foothills zone.

The Himalayan landforms are greatly moulded by the glacial activity and the subsequent deglaciation. The valley glaciers had moved down to lower levels in the past. Moraines are noticed now, but unconnected with any modern glaciers and left by glacial retreat. These morainic materials have been subsequently removed by rivers and spread out as fluvio-glacial deposits. The U-shaped valleys and the broad valleys of Suketi and Jogindernagar testify to extensive Pleistocene glacial action.

A system of terraces developed, particularly during the interglacial periods, when the meltwaters with a lot of glacial and fluvial materials flowed along the valleys and deposited them on either side of the channel floor. Oldest terrace is usually at the top and the youngest, close to the riverbed. The alluvial and terrace material is composed of coarse and loose pebbles and boulders with subordinate amount of sand, silt and clay usually of reddish brown colour. A generalised succession of sediments as seen in this region is presented here (Table 10.24).

Table 10.24. The Quaternary succession in Himachal Pradesh (after Srikantia and Bhargava, 1998, p.147)

Holocene		Alluvium and low terraces
Upper Pleistocene		Kangra terrace, Palampur terrace, Bilaspur terrace Relicts of earlier major glaciation
Middle Pleistocene		Neogal Beds, Boulder Conglomerates
	Upper Siwalik	
Lower Pleistocene and Upper Pliocene		Predominantly conglomerate with minor sandstone and early buff and brown claystone

During the Pleistocene, 3 periods of glaciations referred to as Ruhalkar, Palampur and Kangra affected the area. It is not possible to correlate these with the periods of glaciation well recognised in Europe. Five levels of terraces have been recognised in the Banganga river. A comparison of the relative levels of these at five different localities varies from around 6 m (T5) to about 18.8 m (T1).

Uttarakhand

The Quaternary sediments here have been extensively studied both in

Kumaun and Garhwal Himalaya. Quaternary sediments in the Kali valley of Kumaun, which originates from Lipu glacier (5240 m), have been classified as glacial, glaciofluvial, glaciolacustrine, periglacial and fluvial on the basis of their sediment characteristics, landforms, degree of oxidation and relative relief. The Quaternary lithostratigraphy and morphostratigraphy of the Kali valley is given in Table 10.25. In the absence of any dating (fossils or radiometric) the relative ages have been tentatively assigned based on their relative disposition. The area has witnessed three phases of glaciation as evidenced by three generations of moraines. Five levels of fluvial terraces along Kali river near Dharchula are indicative of at least five phases of rejuvenation in the valley. The terraces mainly belong to Quaternary.

Another interesting study in Uttarakhand is made in Dauliganga basin, which is a tributary basin of Kali in Pithorgarh district, where glacial, glaciofluvial and fluvial deposits have been mapped. Three levels of fluvial terraces have been observed. Tilting of beds with 25° dips northwesterly, microslips, nickpoints and elbow turnings in streams indicate neotectonic activity. The fluviolacustrine deposits occur both in Lesser and Tethys Himalaya of Uttarakhand. Bhimtal palaeolake basin is well known having a 52 m sequence exposed at Garzar between Bhimtal and Naukuchiatal.

Indo-Gangetic Plain

Indo-Gangetic Plain separates the Himalayan ranges from Peninsular India and is made up of thick pile of sediments deposited in the foredeep that developed as a sequel to the collision of the Indian Plate with the Eurasian Plate and the rise of the Himalaya. It extends from Punjab in the west to West Bengal in the east and is made up of sediments brought by the Ganga (Ganges), Indus and Brahmaputra. The deposits are mainly alluvial, though lacustrine and aeolian deposits are also met with. In Punjab, based on shallow surface information, the top part of the alluvium has been classified into seven subdivisions. The aeolian deposits have been classified into three subdivisions, namely older stabilised dunes (O' dunes), semi-consolidated dunes (Sc' dunes) and newer dunes (N' dunes). The current wind direction data point to de-desertification effect in southern Punjab. The palaeowind directions and the morphological features indicate that the dunes in Punjab are northerly extension of the great Thar Desert, but their formation could possibly involve reworking of the local fluvial sediments. These are in parts of Bathinda and Fardikot districts of Punjab. Three fluvial and two aeolian cycles of deposition have been worked out in the Ravi-Beas interfluve sediments in Amritsar district, Punjab. The Older Alluvium comprises multicyclic sequences of sand, silt and clay with calcareous concretions. The second fluvial cycle of deposition includes

Table 10.25. Lithostratigraphy and morphostratigraphy of Quaternary sediments in Kali valley (after Rajesh Kumar and Singh, 2001, p.110)

Age		Lithostratigraphy	Morphostratigraphy	
	Lithounit	Lithology	Morphounit	Landform
Recenet	Kali Recent Alluvium	Grey sand and silt along with gravel, pebble, cobble and boulder	Kali Active Flood Plain (T_0)	Point bar, braided bar etc.
	Recent Alluvial / colluvial fan deposit	Assorted rock fragments in sandy/silty matrix	Alluvial / Colluvial Fan	Fan/cone
	Recent Glacial deposit	Assorted rock fragments embedded in rock flour matrix	Recent Moraine	Cirque, arete, trough, horn kettle hole, trough lake
---------- Disconformity ----------				
Holocene (?)	Kali Younger Terrace Alluvium	Grey to pale, sand, silt and clay along with angular to subrounded gravel, pebble, cobble and boulder size clasts	Kali Younger Flood Plain (T_1 and T_2)	Gently sloping flat surface/ stabilised bar
	Outwash Deposit	Gravel zone along with beds of silt/clay	Glacial/Paraglacial terraces	Outwash plain
	Solifluction Deposit	Angular to subangular fragments of country rock with silt-clay blanket	Solifluctional lobe/cone	Gently sloping surface
	Younger Glacial Deposit	Faceted, assorted, heterogeneous rock fragments in pulverised rock flour matrix	Younger Moraine	Morainic ridge, glacial trough, hanging valley
---------- Disconformity ----------				
Middle to Late Pleistocene (?)	Kali Older Terrace Alluvium	Subrounded to rounded pebble to boulder size clasts embedded in oxidised sandy/silty matrix	Kali Older Flood Plain (T_3, T_4, T_5)	Erosional and depositional terraces
	Valley Train Deposit/ Glacio-fluvial Deposit	Subrounded to rounded, well-sorted cobbles along with few gravel, pebble embedded in oxidised, stratified sediments	Outwash Plain	Gently sloping surface
	Glaciolacustrine/Varve Deposit	Thinly bedded, stratified, silt/clay couplets	Palaeoglacial lake	Levelled to gently sloping surface
	Older Glacial Deposit	Assorted rock fragments in oxidised matrix	Older Moraine	Gently sloping surface
---------- Unconformity ----------				
Pre-Quaternary rocks of Garhwal Group, Central Crystalline and Tethyan Sedimentaries				

reddish brown silty sand sequence and forms the Beas Alluvium. With limited thickness but widespread occurrence these sediments serve as a marker horizon in the Quaternary stratigraphy. The sedimentation of the Beas Alluvium was preceded and succeeded by aeolian deposits, both underlying and overlying the Beas Alluvium. A new fluvial regime forming the third cycle of sedimentation deposited the Newer Alluvium over these sediments. Some of the terms associated with the alluvium in these plains are not formal units.

In Haryana, based on borehole data, the following relatively narrow plain is found to be constituted of (i) Central Alluvial Plain (over the peneplains) and (ii) Older fans and Piedmont, bordering the Siwalik hills.

Age	Formation
Holocene	Aeolian sediments Younger Alluvium of Ghaggar and Yamuna river basins Ambala Older Alluvium of Central Plains
Upper to Middle Pleistocene	- - - - - - - Disconformity - - - - - - - Older Fans and Piedmont - - - - - - - Fault - - - - - - - - - -
Middle Pleistocene to Middle Miocene	Siwalik sediments

(after Thussu, 1995)

The Older Fans occur individually as well as composite units abutting against the Siwalik rocks. These have been observed east of Narayangarh, Raipur Rani and north of Yamunanagar. The fans have a gentle slope of 3 to 5° toward south. Both Piedmont and the Old Fans have been incised by the present day drainage of the Ghaggar river and the Yamuna river. The unit consists of pebble-boulder sequence derived from the Siwalik. The Younger Alluvium has been deposited over the Central Alluvial Plains mainly by the Ghaggar river system. The recent alluvial system is represented in most of the boreholes by grey sand and minor clay lenses.

In the deep interiors of the Sutlej-Yamuna Plains occurs an interesting geomorphic feature tentatively termed "terminal triangular tract (TTT)". These are located at the terminus of and drained by the distributaries of Markanda river in Haryana. They almost look like an inverted delta on the surface. It is differentiated from a true delta by a reversal of gradient near the terminal edge. The feature is more an expression of form rather than of depositional material, which is antecedent to the apparently deltaic form.

In Uttar Pradesh, the Quaternary stratigraphy of the sediments in the

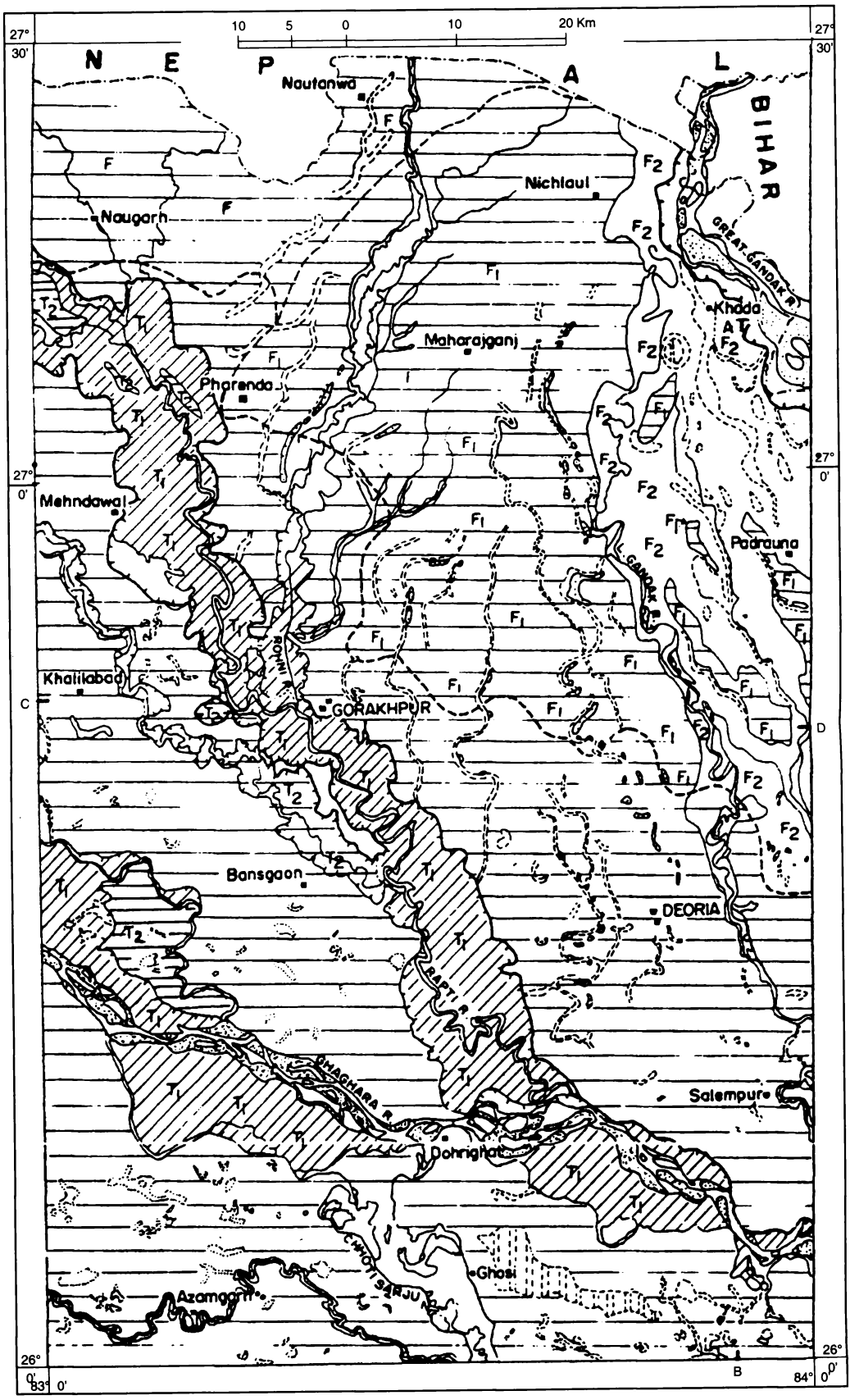
Gangetic Plain is worked out in a little more detail as given below (Table 10.26).

Table 10.26. Quaternary stratigraphy of the Indo-Gangetic plain and Sub-Himalaya, Uttar Pradesh (after Gopendra Kumar et al. 1996, p.812)

Holocene	Newer Alluvium	Active Colluvial Fans Channel alluvium in active channels Terrace Alluvium Alluvial Fan deposits and Palaeo-terrace alluvium	Lacustrine deposits
		– – Disconformity – – – – – – – – – – –	
Middle to Late Pleistocene	Varanasi Alluviuim	Shyampur Fm. of Dun gravels	
		– – Unconformity – – – – – – – – – – –	
Late Pleistocene to early Middle Pleistocene	Northern part Upper Siwalik Group	Dughor (kalar) Fm. (Boulder Congl.) Uttarbari Fm. Marikiri Member — Banda Group	Southern part Chitrakut Fm. Variegated Fm.
		– – Unconformity – – – – – – – – – – –	
Precambrian		Gneissic Complex	

The advent of aerial photographs and imagery has considerably helped to map the various geomorphic features even in apparently featureless plains and this particularly holds good in the Gangetic Plain. Figure 10.15 is a geologic and geomorphic map of an area in Eastern Uttar Pradesh close to Bihar covering part of Ghaghara-Rapti-Gandak subbasins. There have been lots of facies changes within the vast thickness of sediments of the Quaternary and this was interpreted from subsurface lithofacies correlation chart, though they are essentially made up of only sand, silt and clay. That there have been breaks in sedimentation even within the sediments of the Gangetic Plain is well demonstrated from a recent study made near Kalpi, on the Yamuna Plains in southern part of Uttar Pradesh. Variations in the facies assemblages and motifs as well as undulatory contacts between the four major units therein suggest that the inter-unit contacts possibly represent genetic surfaces. These contacts represent hiatuses in sedimentation.

In Bihar, the Old Alluvial Group comprises well-oxidized brown clays, silt and sand with profuse kankar, calcareous nodules and pisolitic iron concentrations. This group is succeeded by thin loess-like aeolian deposits in several parts of Central Bihar basin and then by the more dominant Newer



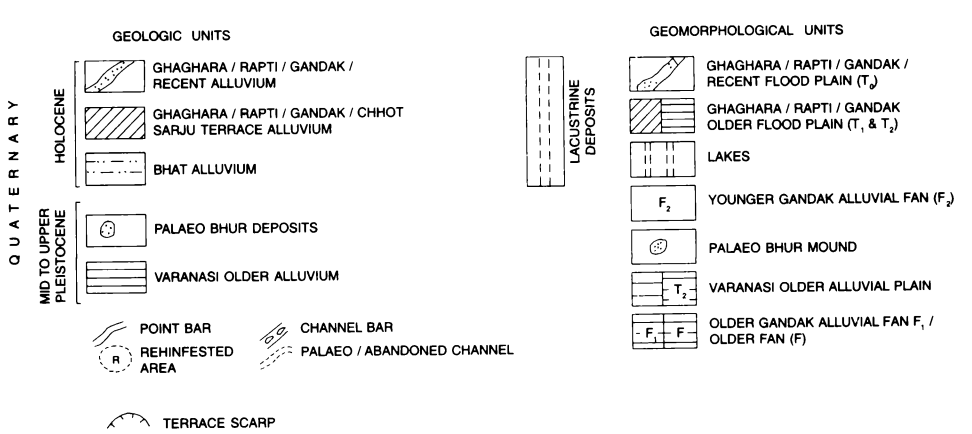

GEOLOGIC UNITS
QUATERNARY
HOLOCENE
GHAGHARA / RAPTI / GANDAK / RECENT ALLUVIUM
GHAGHARA / RAPTI / GANDAK / CHHOT SARJU TERRACE ALLUVIUM
BHAT ALLUVIUM
MID TO UPPER PLEISTOCENE
PALAEO BHUR DEPOSITS
VARANASI OLDER ALLUVIUM
LACUSTRINE DEPOSITS
POINT BAR
REHINFESTED AREA
CHANNEL BAR
PALAEO / ABANDONED CHANNEL
TERRACE SCARP
GEOMORPHOLOGICAL UNITS
GHAGHARA / RAPTI / GANDAK / RECENT FLOOD PLAIN (T0)
GHAGHARA / RAPTI / GANDAK OLDER FLOOD PLAIN (T1 & T2)
LAKES
YOUNGER GANDAK ALLUVIAL FAN (F2)
PALAEO BHUR MOUND
VARANASI OLDER ALLUVIAL PLAIN
OLDER GANDAK ALLUVIAL FAN F1 / OLDER FAN (F)

Fig.10.15. Geological and geomorphological map of parts of Ghagara Rapti-Gandak sub-basins, Uttar Pradesh (after Dwivedi et al. 1997).

Alluvial Group. The latter forms the lower terraces and has a distinctive, though sometimes overlapping lithology comprising unoxidized pale greyish yellow to brown silt, clay and sand. Present day sediments comprising unoxidized sand, silt and clays overlie and embay into the younger alluvium along stream courses, channels, levees and swamps. Still younger sequence consists of the Older and Younger Flood Plains. Old Alluvial Group is generally placed in the Middle Pleistocene, the Newer Alluvial Group in the Upper Pleistocene to Holocene and the Older and Younger Flood Plains in the Early Holocene to the Present. Gandak and Kosi Mega Fans are very prominent landforms in North Bihar, representing one of the largest "inland deltas" in the world. The Gandak megafan has been classified into 10 geomorphic units, west to east over a distance of 105 km. What is interesting is that each of them is associated with a characteristic soil. It is their distinct reflectivity that has enabled distinguishing them. Seven units are identified in the Kosi fan. Both the Kosi and the Gandak are noted for channel migration caused by autocyclic and neotectonic changes. The Kosi has avulsed from east to west by some 120 km of the megafan in 220 years. The Gandak has avulsed from west to east over a distance of 105 km.

In West Bengal, as elsewhere in the Gangetic Plain, Older and Newer Alluvium are recognised. The Older Alluvium contains abundant proportion of calcareous and limonitic nodules. Organic material in the Alluvium is commonly confined to the surface soil profile. These sediments include the Barinda Formation in the northeast part of the Bengal basin as a whole, and the Pleistocene terraces in the western part. Though a great part of Barinda falls beyond the limit of the state into the adjoining Bangladesh, these are partly developed in the adjoining districts of West Dinajpur and Malda. In the northern part, the piedmont alluvium plain overlaps the Pleistocene flood plain deposits of Barinda tract of the Jalpaiguri and Darjeeling districts. Estuarine deposits, flanked by mangrove swamps and mudflats, consist of a succession of grey clayey silts with plant matter, silt and sand, which include foraminifera such as *Rotalia trisponosa, Thalmana, Haplophrag moides, Trochamina* as well as tidal foraminifera. Subsurface peat beds are characterised by spores and pollens indicating an age within the time range of Pleistocene and Holocene.

The Ganga basin, which is in one sense a part of Indo-Gangetic-Brahmaputra plains, encompassing an area of 3,00,000 sq.km is mostly covered by alluvium. Subsurface data from wells drilled, along with seismic and laboratory data, have been used for reconstructing the lithostratigraphy of the basin. Two major sedimentary cycles separated by a pronounced unconformity and concealed below alluvial cover represent the entire stratigraphic column of Ganga basin. It may be noted that over the granite basement of Archaean,

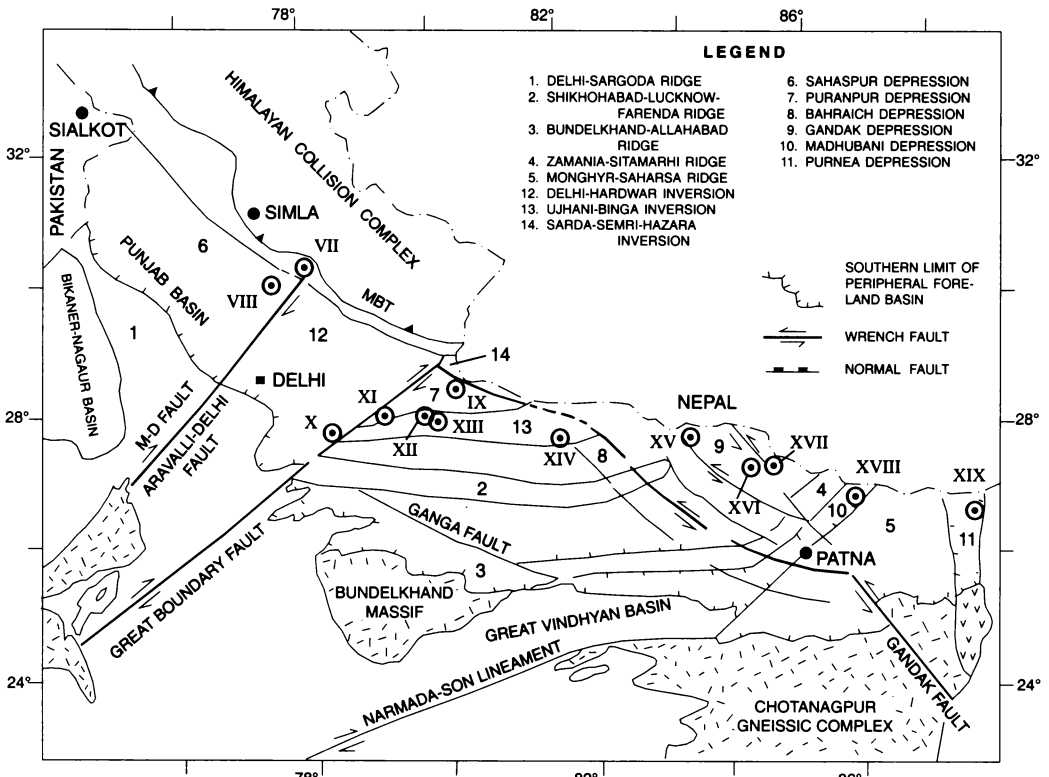


Fig.10.16. Tectonic map of Ganga Basin. VII - Mohand-1; VIII - Saharanpur; IX - Purnapur; X - Kasganj-1; XI - Ujhani-1; XII - Tilhar-1; XIII - near Tilhar; XIV - Matera; XV - Ganauli-1; XVI - Gandak-1; XVII - Raxaul; XVIII - Madhubani-1 and XIX - Purnea-1. (Well XV to XIX fall in Bihar State). Abbreviations: MBT - Main Boundary Thrust; M-D Fault - Mahendragarh-Dehra Dun Fault (data from Pramanik et al. 1996; Fuloria, 1996) (after Shukla et al. 1994) (source: Mahadevan, 2002, p.406).

formations possibly equivalent to the Vindhyan Supergroup are represented. After a great hiatus, possible Paleogene (Matera Formation) sediments are met with followed by distinct Neogene sediments referable to the Siwalik Group.

Study of the depth contour map, on top of the basement under the Indo-Gangetic Plain, as estimated from aeromagnetic data, shows a thickness of over ~7620 m near the mountain front. However, it is only around ~1500 to 3000 m in the southern side, closer to the Precambrian Peninsular shield, with wide variation and irregular disposition with numerous closures. This is a result of the basin being made up of ridges and depressions (Fig.10.16). Among the ridges the Faizabad ridge was one, which has been uplifted in a step like manner along different cross-faults, while on the east, horst and graben structures are to be met with.

The basin is made up mainly of clastic sediments developed as a result of collision of India-Eurasian continental plates during Paleocene. Collision resulted in overthrusting along Main Central Thrust, raising the Higher Himalaya to form source rocks for the sediments to be deposited in the 'foredeep' created south of it. With passage of time more southerly areas were also raised shifting the depocentres further south. There was also overthrusting along the Main Boundary Fault. These phenomena are reflected in the presence of a coarsening up megacycle with at least two superimposed minor cycles and in the composition of the sandstones and conglomerates of the basin. Later folding of the northern edge of the basin to form the Siwalik Ranges during the Early Pleistocene led to cannibalism of this part of the basin. Ganga basin is a polyhistory foredeep with superposed geotectonic set-ups at different stages of evolution.

Correlation of the Quaternary sediments in different sections of the Indo-Gangetic Plain from Punjab to West Bengal is rendered difficult due to the absence of index fossils. Though some C isotope dates are available, no complete picture of correlation has evolved.

Jharkhand

Between Rajdanda (Lat. 23°25'00": Long. 84°07'30") in West Bengal and Mahuadnr (Lat. 23°23'25" : Long. 84°06'40") is exposed Rajdanda Formation, along the western fringes of the Ranchi Plateau in the Mahuadnr valley along the Birna, a tributary of the North Koel river. Comprising a succession of conglomerates, shales and sandstones, these overlie Chotanagpur Granite Gneisses and are considered to be of Quaternary age. Besides these are large areas west of Ranchi covered by alluvium which is assigned a Quaternary age. These are similar to the Rajdanda alluvium.

West Bengal

There are sediments of the Quaternary both near the foothills of the Himalaya as well as in the vast plain around the rivers of Damodar, Bhagirathi and Ganga. A detailed study of the morphological features, particularly of the lateritic surfaces, valley cuts and fills, terraces and plains and mutual relations between them has resulted in the tracing of the geologic/geomorphic history of a part of coastal plain around Burdwan, West Bengal. The study was mostly based on airphoto-interpretation with limited field checks. Figure 10.17 is the geological-cum-geomorphic map of the area around Burdwan in West Bengal. It may be seen that the formations range in age from Middle Pleistocene to Holocene. These formations have been compared with similar ones in Midnapur and also Baitarani valley in Orissa. The following is an attempted correlation among the formations recognised here (Table 10.27).

Table 10.27. Correlation of Quaternary Formations in coastal plain of West Bengal (after Niyogi, 1975)

Geomorphic Units	Age	Geologic Units		
		Baitarani Valley	Midnapur	Burdwan
Recent deltas and Terraces	Holocene	Chandbali Formation	Digha Formation	Nabadweep Formation
Younger deltaic plain and corresponding terraces	Late Pleistocene	Jaipur Formation	Kanthi Formation	Kalna Formation
Older deltaic plain and corresponding terraces	Late Pleistocene	Soro Formation	Belda Formation	Kusumgram Formation
Lateritic Upland	Mid Pleistocene	-	Kharagpur Formation	Worgram Formation

Assam

It was Maclaren who, almost in the beginning of the twentieth century, recognised the Pleistocene river terraces in the Brahmaputra Plain. Dihing Formation, which is essentially made up of Quaternary mountain front deposits, passes into what is called Dhekiajuli Formation, made of soft sandstones, bordering the Naga Thrust. The same beds have also been met within most of the wells in Upper Assam valley (i.e. the Brahmaputra Alluvium). Dhekiajuli is primarily a group of soft sandstones with impersistent bands of clays and

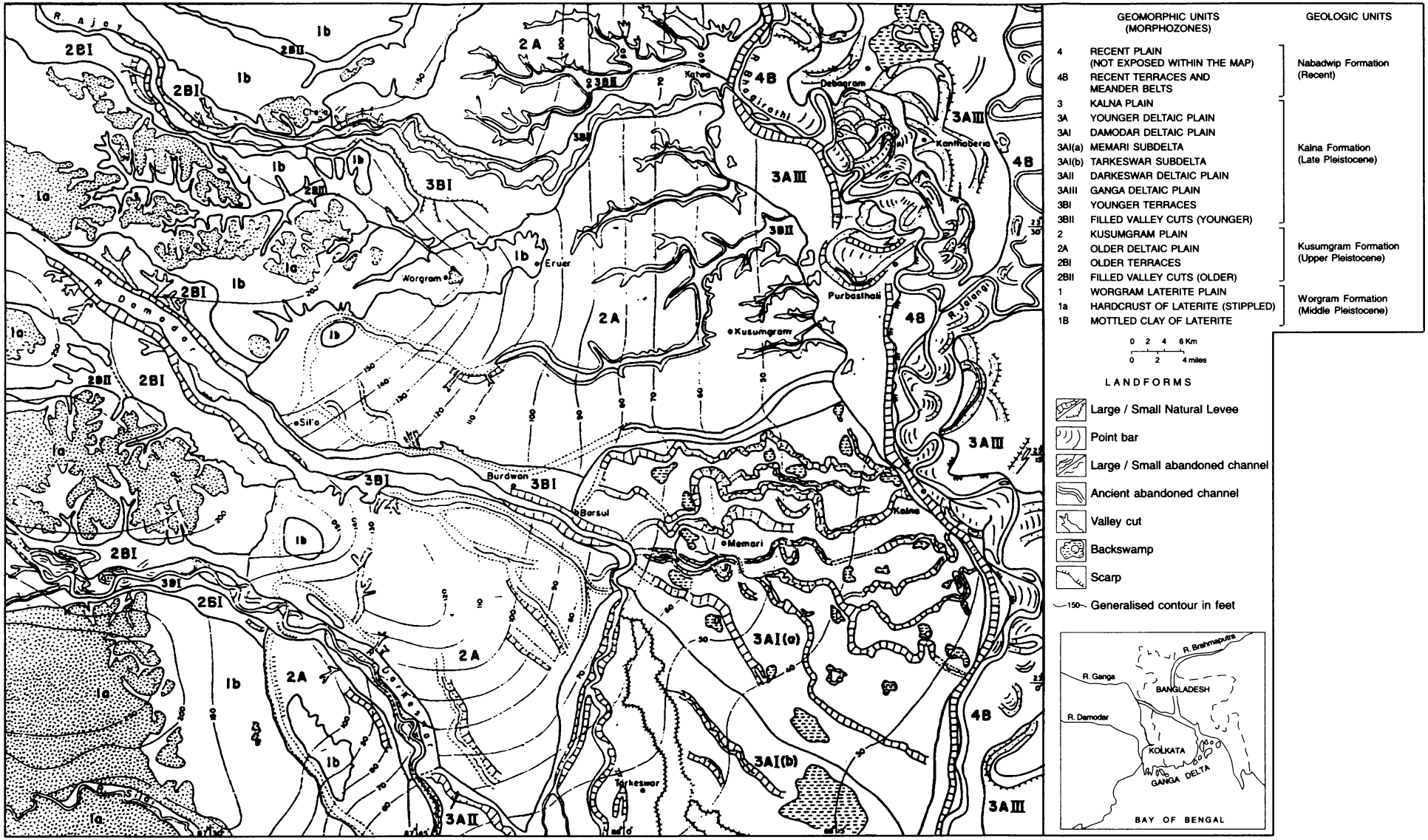


Fig.10.17. Morphogeologic map of the area around Burdwan, West Bengal (after Niyogi, 1975; Reprinted with permission from IJES).

silts. The Alluvium and Dhekiajuli have a combined thickness varying around 1300 m in front of Naga Thrust near Jaipur. This increases further north around Nahorkatiya from about 1560 m to around 2180 m north of Subansiri mouth, all met with in wells drilled in these areas.

Alluvium, the youngest of the sediments belonging to the Holocene, are of varying thickness and content depending upon its location with respect to its provenance. There have been quite a few post-Dihing (post-Pleistocene) uplifts, which have affected the trend and lie of the numerous river terraces that were formed during Pleistocene-Holocene in the Brahmaputra valley and also those of its major tributaries. As many as six terraces have been recognised from the Jaldhoka valley of north Bengal. Incidentally this is the region of an enormous submontane fan built by the Tista and its neighbouring rivers, which is possibly one of the largest fans in the world. The alluvial deposits in Assam range from extensive terrace forming boulder beds to sands, silts and clays. The youngest alluvium forms the present day flood plains.

Arunachal Pradesh

During the Himalayan orogeny and simultaneously with the development of the Subhimalaya and the Arakan Yoma Mountains in early Middle Pleistocene, a depression was formed between the raising mountains. This valley or basin, referred to as the Brahmaputra valley, was filled up by fluvial or fluviolacustrine sediments during the later part of the Quaternary and evolved as a plain – Brahmaputra Plain.

Broadly two cycles of sedimentation have been recognised, the first constituting the Older Alluvium and the second referred to as the Newer Alluvium. The Older Alluvium is deposited in the form of 2 to 3 terraces. The youngest terrace adjoining the river is the widest and used for both extensive cultivation and habitation. The upper age limit of this cycle of deposition is considered to be Late Pleistocene around 17,500 yrs B.P.

The Newer Alluvium is the last ongoing cycle of sedimentation, which was initiated, in the form of large fluvial fans at the mouth of different rivers, which define the flood plains and limit of Holocene basin. The radiometric data indicate commencement of this cycle of sedimentation around 10,000 years B.P. In fluvial channels, sediments constitute the river terraces.

Orissa

The laterites, residual soils, marine sediments and minor occurrence of volcanic ash beds represent Pleistocene in Orissa. The low-level coastal laterites are believed to be of Quaternary age, while the high-level bauxites and laterites

could be older (Eocene?). Pleistocene sediments have been recognised from borehole data (in the southwestern part of the Mahanadi delta) and dated as varying from 40,000 to 20,000 years B.P., made up of marine, fluvial and lacustrine sediments.

A few ash beds of volcanic origin have been recorded in Vamsadhara-Nagavali and Mahanadi-Brahmani river valleys. It is believed that they have an affinity with Toba volcanic calderas of Indonesia belonging to an age of 74,000 years B.P. It has been designated as Young Toba Ash (YTA). The ash beds consist of angular to very angular glass shards and pumice, with minerals like quartz, biotite and feldspars.

Besides the above, Quaternary sediments are met with in both coastal tracts and upland river valleys (Table 10.28).

Table 10.28. Quaternary lithostratigraphic sequence in coastal Orissa (after Pradhan, 1998, p.97)

Present Day (Recent) Fm.	Floodplain outwash and channel deposits
Bankigarh Fm.	Semiconsolidated and loose older deltaic deposits of sand and clay; 1590, 1220±120 yrs. BP
Kaimundi Fm.	Partially consolidated floodplain sandy clay deposits (caliche bearing); 4250±120 yrs. BP; 5880±120 yrs. BP
- - - - - - - -	— Paraunconformity / Disconformity - - - - - - - - - -
Bolgarh Fm.	Laterite and Latosol
	— Paraunconformity / Disconformity - - - - - - - - - -
Naira Fm.	Sandstone, gravel/pebble bed associated with the YTA ash bed Age of the ash bed: 74,000 yrs. BP
- - - - - - - - -	- - Unconformity -
Tertiary and older rocks	

Chilka Lake represents a part of the sea, first rendered shallow by deposits from the mouth of Mahanadi and then cut-off from the sea by a long sand spit produced by the monsoon winds during the Pleistocene (Fig.1.7). The lake is gradually diminishing in its extent. There is a deposit of estuarine shells 6-9 m above the high tide level on the southwest end of the sand spit, which indicates emergence. These shells include *Meretrix casta, Sunetta scripta, Arca granosa, Potamides angulatus* and *Cuma disjuncta.*

Andhra Pradesh

Quaternary deposits are well developed along the east coast of Andhra Pradesh, especially near the mouths of large rivers such as Godavari, Krishna

and Penner and in narrow belts bordering their inland courses and also those of many smaller rivers passing through the state and discharging into Bay of Bengal. The deltas of Godavari and Krishna rivers are conspicuous in the map of Andhra Pradesh with distributaries, lagoons, ancient beach ridges and abandoned channels and are referable to Quaternary. Though mapping of these landforms (Fig. 10.18) has been done using mainly aerial photographs and imagery, the lithostratigraphy of the Quaternary has not been firmly established. Subsurface data has confirmed Mio-Pliocene sediments and hence the deltaic sediments are referred to the Quaternary. Krishna delta is subarcuate to lobate, whereas the Godavari is arcuate. In both the cases the stages of progradation have been traced, based on the mutual relations between the geometry of the abandoned channels and ancient beach ridges.

The fossiliferous horizon from Gundlakamma and Munneru river basins containing skulls, mandible, limb bones, and horn cores of the species Equus, Sus, Cervus, antelope, bovid and a part of the skull of *Crocodylus palustris*, post-dates the youngest Toba tuff. A late Pleistocene to early Holocene age is suggested for the fossils contained in the sediments of the valleys. A rich vertebrate faunal assemblage of Rhinoceras, Boselaphus and Cerus are identified for the first time in recent years within the flood plain of river Pampa suggesting grassy plains dotted with trees and shrubs in Pleistocene times. Volcanic ash bed also occurs in the Pampa river valley.

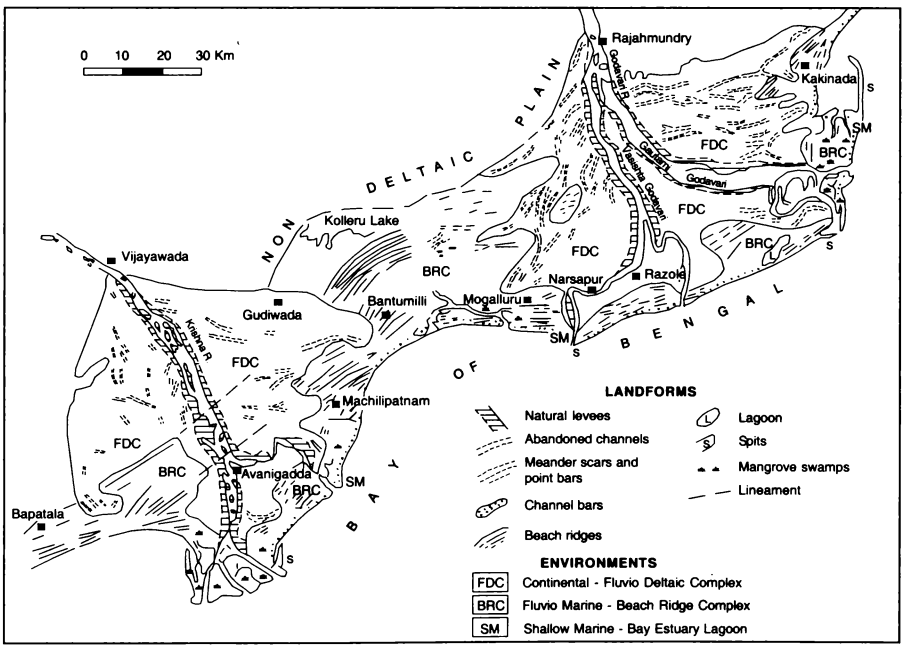


Fig.10.18. Geomorphological map of Krishna-Godavari deltas (source: Biswas, 1993, reprinted with permission from Current Science).

In the Kurnool district, a group of ossiferous caves known as Billa Sargam caves are formed in the limestones of the Kurnool Group (Neoproterozoic). The floors of these caves are encrusted with stalagmites, which are underlain by red marl full of animal bones of apes, mammals, birds, reptiles, and carnivores, which indicate an upper Pleistocene age. Microvertebrates like rodents and bats, limb bones and mandibles of cervids, dental remains of primates, molar tooth of presbytes, carnivores, insectivores etc. have been recovered from the deposits of some caves. The most significant discovery was fossil human mandible and four isolated teeth in the Mogasarayanigondi cave near Betamcherla in Kurnool district.

Tamil Nadu

The fluvial, fluviomarine, aeolian and marine Quaternary sequences occupy a total area of about 22,750 km^2 mainly along the east coast and along some of the major river valleys (Fig.10.7). An arenaceous sequence of Holocene age called Coromandal Formation is reported to occur below the coastal beach sand in the northern coast of Chennai and Tiruvallur districts. Around Kancheepuram, an arenaceous formation consisting of pebbles and shingles of quartzites, vein quartz etc. referred to as Conjeevaram (Kancheepuram) gravels of probable Pliocene to Lower Pleistocene age is exposed. Calcareous mud, clay, calcareous sandy clay and gritty sandstone occur in Kambam Valley in the western parts of Theni and Madurai districts. These fresh water sediments occupy elongated NNE-SSW trending structurally controlled basins. Further south, beds of open-textured loosely indurated coarse calcareous gritty sandstones and shell limestones are found in the coastal tracts of Tuticorin district. These are mostly covered by red "Teri" sands of Quaternary age some containing early human tools (see p.888). Similar occurrence of calcareous gritty sandstone recorded near Soyamali in adjoining Tirunelveli district carries vertebrate fossils of Pleistocene age.

Teri sands, lying some distance away from the modern shores in the south-eastern districts of Tamil Nadu – Ramanathapuram, Tuticorin and Tirunelveli – form large barren waste lands of high mounds and ridges composed of piles of reddish dunes with intervening depressions. It is made up mainly of reddish stained quartz with an admixture of fine red clayey dust and fine grains of ilmenite. The thickness of the Teri sands increases landward from about 1.5 m to a maximum of 7 m. Evidence suggests that in all locations, the red dunes were deposited in the Late Pleistocene and reddened by weathering of *in situ* feldspar, amphibole, pyroxene and iron rich garnet in the Early to Middle Holocene. The weathering led to the formation of latosols with up to 40% clay-sized fraction dominated by kaolinite and illite, and released free iron oxide.

In Ramanathapuram-Tirunelveli areas the alluvial deposits form 15 m high terraces above the recent floodplain. The Soyamali fauna of Tirunelveli district includes *Lissemy punctata*, *Stegodon insignis*, *Bos namadicus* and *Elephas hysudricus* The coastal marine deposits are the large linear tracts of beach sand with shell fragments forming raised beach terraces representing the present and palaeoshorelines. The soft black clay carrying marine shells occurring in a number of backswamps, tidal flats, lagoons and estuaries.

Coral-algal limestone exposed near Rameshwaram and Mandapam islands have assumed great significance in paleoclimatic and sea-level studies.

Kerala

Quaternary deposits of Kerala are mainly of the brackish water and lagoonal environments. Black clays, shell beds and beach sands occur over a large area of the southern coast of Kerala. The beach sands of Chavara and Manavlakuruchi contain radioactive minerals. The other Quaternary deposits encountered are peat beds of both marine and fluvial environments, sand bars, sandy flats, raised sand beaches, and reddish sandy loam, known as "Teris" near the coast. The Teris are fine to medium grained containing heavy minerals like ilmenite, zircon and hematite. These are extensions of those found in southeastern Tamil Nadu coast.

One of the important and peculiar deposits close to the shore along the Kerala coast usually formed during the southwest monsoon season is the Mud Bank. Most of these seem to occur at the mouth of rivers and lagoons.

Karnataka

Major rivers of Karnataka, namely Krishna, Cauvery, Tungabhadra and Bhima have formed fluvial terraces. These terraces are made up of gravel and sands. The higher elevations of these terraces are ascribed to slow episodic uplift of land in recent times. Mammalian remains have been found in the alluvium of Krishna and its tributaries. Large number of chipped quartzite implements has been found in various gravels of Malaprabha and other tributaries of Krishna.

Wave-cut caves in laterite at different elevations along the west coast are common, testifying to the recent changes in sea level. Most of the sheltered creeks and lagoons show accumulation of lime and oyster shells. St. Mary Island off Malpe along the west coast has wave-cut platforms at different elevations, the highest being 10 m above present-day sea level. The other terraces are approximately at 6, 3 and 1.5 m.

The lower levels of the Arabian Sea – the submerged terraces on the western continental shelf between 11 and 20° Lat. at -92, -85, -75 and -35 m may be stillstands in the Flandrian transgression, which followed the maximum of the last glacial regression.

Maharashtra

Quaternary deposits of Maharashtra are represented by alluvia deposited by the rivers. The major alluvial deposits are those in the valleys of Tapi, Purna, Godavari, Wardha, Penganga and Wainganga rivers. The Tapi valley alluvium covers an extensive plain, about 240 km in length in an E-W direction in Khandesh. The width of the plain at places is 50 km. It is mainly to the north of the river. In the southeast the plain is connected by about 32 km long belt with the alluvial plain of Purna river, which is a tributary of Tapi river. Godavari alluvium is conspicuous particularly between Nasik and Paithan – about 200 km in length and 50 km in width. Four major phases of fluvial activity, since late Middle Pleistocene are inferred. These rivers were dominantly aggrading during the Late Pleistocene (i.e. 40,000 – 11,000 years B.P.) and incision predominated during the major part of the Holocene. These changes in the fluvial activity in western Maharashtra upland rivers are explained in terms of climatic changes during late Quaternary.

Besides coastal alluvial deposits restricted to the numerous streams flowing from the Western Ghats (Sahyadri) into the Arabian Sea, there are beach rocks occurring as isolated patches along the coast and comprise conglomerates, shell limestone bands and consolidated dune sand, designated as "karal". The karal has been dated and found to range from Middle to Late Holocene in age. The fauna recovered from the beach rock comprises mollusca, foraminifera, broken fragments of bryozoa, corals etc. Occurrence of possible evaporite gypsum in sub-bottom Holocene sediments off Ratnagiri is ascribed to evaporation of seawater isolated during regressive phases of the Quaternary.

From the alluvial deposit along the Godavari valley between Nasik and Paithan a large number of vertebrate bones have been reported. *Elephus antiques* is one such species. Other fossils recorded are the lower jaw of a Hippopotamus, *H. (Tetraprotodon) palaeindicus*, a tooth of *Equus namadicus*, bones of Bos, crocodile teeth and several molluscan shells.

Andaman and Nicobar Islands

Volcanic activity in the Indian Quaternary is restricted to the Barren and Narcondom islands in the Bay of Bengal. These fall in line with the Sunda chain of the present day volcanoes. Barren Island has the shape of a symmetrical cone, which is encircled, by an amphitheatre of about 3 km in diameter rising

about 100 m above sea level. The height of the lava cone above sea level varies from 180 to 335 m. The Narcondam Island is oval in shape and rises 700 m above the sea level from comparatively deeper waters of the Bay of Bengal. It has an area of about 10 km^2. It has no crater, which may suggest domal form of eruption. Some volcanic matter occurs interbedded with the surrounding rocks of the Irrawaddy Group, which may indicate the time of its eruption as far back as Pliocene.

In the Andaman Islands Rutland Conglomerate and Shell Limestone are noted mostly around southern and western coasts of Rutland and Turn Islands. The limestones are essentially made up of shell fragments, mostly of corals, lamellibranchs, gastropods, echinoids, and crinoids together with pebbles of various rock types, in calcareous cement. Shell limestones occur on the southern and southeastern coastline of Great Nicobar Island as raised platforms. Much of these are covered inland by raised beach sands. These limestones are tentatively considered to belong to the time interval of 6000-4000 years B.P. to Holocene. Perhaps the youngest are the raised shell/coralline beach seen both along the coastline as well as inland, sometimes about a kilometre or two from the present coastline and at various altitudes up to 15 m above the present sea level. These are also partly covered by soil mantle. Contrary to the earlier belief that the Andaman islands may be submerging, these deposits suggest rising of the island.

Lakshadweep (Laccadive) Islands

The Lakshadweep group of islands is scattered in the Arabian Sea about 200 to 400 km off the west coast of Kerala. The general topography of the islands is hummocky to flat with steeper shore on the east. The coralline islands are fringed by beach material all around them. They are largely composed of coarse sand, disintegrated coral, shell fragments and uncemented pebbles, shingles, cobbles and boulders. The western side of most of the islands is fringed by coralline reef enclosing a lagoon. Isotopic and elemental tracers, incorporated in the carbonate skeletons of these corals during growth provide proxies of past environmental variability of the surface ocean.

QUATERNARY TECTONIC ACTIVITY

Neotectonic activity during the Quaternary has been inferred from different sources of evidence. These include mainly aspects of fluvial/ riverine morphology, as rivers are sensitive to every small change in physiography and structure. Riverine morphological evidences include rejuvenation of meandering streams, spectacular knee bend in an otherwise straight valley, meandering

streams that fall and cascade down steep scarps, abrupt changes in the longitudinal bed rock profile of the river, reversal of drainage, dissected buried channels, derangement of streams, lateral shifting of stream courses along parallel or en echelon lineaments, knick points at a constant distance from a range, unfurrowed straight planar valley slopes, faceted spur along a mountain front, upstream ponding (tectonic lakes), downstream accentuated channel incision with respect to lineaments/faults and large thickness of alluvium and its truncation as revealed from isopach lines.

Structural evidences include angular unconformity between Older and Younger Alluvium, folding of recent alluvial gravel, tilting of fault-bound blocks and terraces, folding in lava flows, thrusting of different units of older formations over recent alluvium – particularly in the Himalaya, abrupt termination of a set of ancient beach ridges near a coast and juxtaposition of alluvial cones and alluvial fans in some tectonic domains. Recurrent seismicity and occurrence of hot springs and high conductive heat flow also indicate neotectonism.

Numerous evidences of neotectonism reported indicate that no part of the country seems to have been spared from its effect. Some select examples are given here.

Gujarat: Between Vaitarna and Alibagh through Mumbai, the raised beaches record uplift of the order of 6 m. In the southeastern part of Saurashtra on the two sides of the Hiran valley, the Pleistocene miliolites are reported to occur at heights of 75 m at Umrethi and 104 m at Shingawado, indicating differential movement along an active fault that follows the riverbed. The Okha-Rann fault in Saurashtra is marked by a 20-40 m high cliff of the Gaj (Miocene) and Dwaraka (Pliocene) beds. The youthful topography of Kutch is a clear indication of the differential tectonic uplift during Quaternary. Deformed alluvial sediments in Narmada and Mahi river basins and drainage configuration suggest reactivation of pre-Quaternary faults. Palaeoseismic events reported from Great Rann of Kutch and lower Mahi valley together with the present day seismic activity in Gujarat indicate the active nature of the various faults.

Central India: In the Narmada valley between Jabalpur and Hoshangabad the Quaternary sediments have been displaced, and the transverse Navagam Dam Fault has shifted the Bagh Beds. In the region of Tapti-Satpura lineament numerous evidences of neotectonism have been observed among which are (i) tilting of various fault-bound blocks up to 30°, (ii) occurrences of hot springs, (iii) reported earthquakes in Jalgaon region and (iv) high conductive heat flow (97-135 mW/M^2) in the vicinity of Satpura foothill fault at Salbardi.

Rajasthan: Reactivation along older faults have affected drainage trends

particularly along the Aravalli foothills and have resulted in drainage anomalies like channel branching or obliteration, channel incision and shifting of courses. Knickpoints on profiles of west flowing rivers, remnants of old valleys, abandoned flood plains and multi-tier terraces in the piedmont areas close to the hills indicate the effect of neotectonism. Some of the lakes are associated with different types of faults within the grabens. Large lakes like Didwana and Sambhar occur on the trace of curvilinear strike-slip faults. The neotectonic uplift of the Aravalli Range has produced at many places, as near Sandra, recent alluvial cone deposits, against active fault escarpments.

Himalaya: Major rivers in the Himalaya cross the mountain barriers (7000 – 8000 m) and enter the Lesser Himalayan domain through deep canyons and have high gradients with many knickpoints within the stretch of the Main Central Thrust zone (MCT). These features imply very brisk rate of uplift of the Himadri (0.7 to 1.1 Ma). There are numerous examples of older Himalayan rocks advancing and riding over Sub-Recent and Recent deposits all along the southern margin from Jammu in the northwest to Arunachal Pradesh in the northeast. It may be noted that in some cases radiometric dating has been done of some of the tectonic lineaments along which carbonaceous material was encountered. These gave ages ranging from around 40,000 to 20,000 yrs B.P., indicating they were mostly of Late Pleistocene times.

Ganga Plain: Numerous anomalous drainage patterns, tilted terraces, sudden changes in the soils and many piracies in parts of the plain have been located mainly through interpretation of aerial photographs and imagery. Survey of India has run a number of high precision levelling lines across the Indo-Gangetic Plain and repeated over the last 100 years or so and the inference is that there have been differential uplift and subsidences in parts of the plain.

Assam: Brahmaputra earlier flowed close to the foot of the Meghalaya Plateau, and through the Sylhet basin, into the Meghana river in eastern Bangladesh. More than two and a half centuries ago, it flowed past Mymensingh. But between the years 1720 and A.D. 1830 it swung westward and joined the Ganga presumably as a consequence of the uplift of the Barind-Madhupur tract in central Bangladesh. The Tista, which used to be an affluent of the Ganga, suddenly swung eastward in A.D. 1781, to become a tributary of the Brahmaputra. The rivers changed their courses as a result of uplift or subsidence of the ground on which they flowed.

West Bengal: In the Calcutta-Sunderban coastal areas of south Bengal borehole data reveal repeated upheaval and subsidence of the depositional basin

(Bengal basin) owing to neotectonic movements. Occurrences of peats and calcretes, which can form under different environments only and at different levels is indicative of movements, horizontal as well as vertical. Some of these may be due to eustatic changes in sea level. Concentric pattern of a five-tier lobe surfaces on the deltaic plain is considered to be the result of gradual rising along with progradation of the delta front in the recent past (presumably over the past 5000 years).

Orissa: Near Balasore, a stretch of 320 km of the Orissa coastline was uplifted within human memory, rendering useless the historic port of Balasore and pushing an older cliff about 16 km inland from the present shore.

Andhra Pradesh: There is a major ENE-WSW lineament in the southern part of Godavari delta. Where the three distributaries of the Godavari river – Gautami, Vasishta and Vainateyam cross this lineament, their drainage trend is obliterated indicating continuous movement along this lineament. In Anantapur district, the Precambrian granites and gneisses are affected by a number of faults, some of which could be very old. However, there is a NNW-SSE fault, east of Puttaparti, along which faceted spurs, hanging valley and stream piracy can be seen. These are indicative of faulting sometime during the Quaternary.

Tamil Nadu: The ponding of streams over the Nilgiri massif due to reactivation of faults seems to have given rise to lakes, which contain 20,000 to 5,000 year old peat with black clays. Thrusting up of the Nilgiri block on the E-W oriented Moyar shear zone (which separates the Southern Granulite Terrain from the Dharwar Craton) is considered to be a continuing process. This is inferred from the rejuvenation of meandering streams, presence of unfurrowed straight planar valley slopes and development of numerous deep defiles and waterfalls.

Near Pondicherry, an 11 m thick lignite bed is found at a depth of 72 m, and near Volimukkam in Tirunelveli district, submerged forest is found just below high water mark.

Kerala: Occurrence of laterite along the beach near Kollam and north of Kozhikode and the reported occurrence of laterite and Warkalli Beds below the present sea level (boreholes of CGWB, north of Kollam and east of Ambalapuzha) are positive evidences of neotectonism. Abutting of strandline against the Pamba river north of Harippad, and Perumba river south of Payyanur, and the reported occurrence of submerged forest east of Kudavechur and west of Harippad are other evidences of neotectonism.

Karnataka: The unusual coast-parallel bends of west flowing rivers, particularly in southern Karnataka, are guided by longitudinal coastal faults. Parts of southern Karnataka seem to have been affected by en echelon faults giving rise to isolated fault blocks. For example, the Biligirirangan-Mahadevara Malai hills are considered to represent fault line horsts. They are drained by streams, which meander over them, and fall and cascade down their slopes. There are cases of knee bends in the direction of flow of streams. In a few places fluvial gravels show minor folding. From its original southeasterly course Cauvery river abruptly shifts northward. All the above are considered to indicate Holocene movements on the faults delimiting the horsts.

Maharashtra: The Western Ghat escarpment (of the *Sahyadri* mountains) appears to some to be a resequent fault line scarp, though many consider it as simple recession due to headward erosion of many streams flowing due west. The ENE-WSW faults/fractures seem to be younger as they truncate or offset the NNW-SSE and NW-SE trending lineaments. Near Mumbai a large number of autochthonous tree trunks of *Acacia catechu* have been found in the blue clay about 6 m below the sea level. The subsidence of the shore is indicated.

Offshore: Bathymetric and shallow seismic data from the continental slope off Saurashtra-Mumbai indicate wide submarine terraces at 130, 145 and 170 m and reefal structures at 320-360 m water depths. 10 cm thick slabs of limestones are recovered from 130 m-depth terrace. The age of the limestone is 11,900 yrs. B.P. These imply that the 130 m-depth terrace was at intertidal depths at about 12,000 yrs.B.P. The eustatic sea level, however, was at –90 m at 12,000 yrs. B.P. This disparity suggests neotectonic activity and subsidence by about 40 m on the Saurashtra-Bombay region sometime after 12,000 yrs. B.P.

QUATERNARY CLIMATIC CHANGES

Variations in climate played a major part in the disposition and nature of sediments during Quaternary in different parts of India. Strong tectonic movements at the beginning of Quaternary and at 0.8 Ma influenced the accumulation of enormous volume of sediments in the Siwalik Range and Bay of Bengal. The Himalaya attained greater elevation and caused diversion in the flow of moist winds and created large cool areas conducive to precipitation of snow. Cold climatic conditions that had started 2.5 to 3.0 Ma ago in the northern hemisphere culminated in the glaciation of higher mountains in the Pleistocene. The rapid uplift of Tibetan Plateau (3500 by 1500 km and more than 5000 m high), since the Middle Miocene, perhaps caused the single major change in monsoon circulation, by creating high and low pressure centres.

Deglaciation started in Kashmir around 18000 years B.P. as indicated by the broad-leaved elements in the pollen profile, development of palaeosols, C3 type plants and an Upper Palaeolithic culture. Climatic amelioration at c.18000, c.15000, c.1300 and c.1000 years B.P. in the Kashmir valley is indicated by both pollen and pedogenic evidence. The varve deposits at Goting, district Chamoli, Garhwal Himalaya (Uttaranchal) have recorded climatic history of the Last Glacial Stage (LGS). ^{14}C chronology indicates that the deposition commenced around 40 Ka B.P. and continued till the glacial maxima (about 20 Ka).

Study of tropical peats in south India has given indications of climatic change during Quaternary. Stable isotope ratios of carbon in soils or lake sediments and of oxygen and hydrogen in peats have been found to reflect past moisture variations and hence provide valuable climatic records. Based on some samples collected from the peat bogs in Nilgiri Mountains, an arid phase between 6 to 3.5 kyr ago and wet phase 600 years ago could be delineated. The latter appears to correspond to the Mediaeval Warm period, which previously was believed to be confined to Europe and North America.

A striking example of southerly shift of climatic zones is represented by the present day disjunctive distribution of *Hemitragus hylocrius* (the Nilgiri goat), which is a near relative of the *Hemitragus jemlahicus* (Himalayan tahr) whose ancestors were fairly common in the Pleistocene. The occurrence of some rhododendron species in Peninsular India is ascribed to similar factors. Overall, the climate and vegetation in the high altitude regions of the southern Indian tropics seem to have responded to past glacial climatic changes and this is consistent with other evidences from India and other tropical regions.

QUATERNARY SEA LEVEL CHANGES

Sea level is of great concern to human beings especially to those living in coastal regions. India has the sixth longest coastline in the world (>7500 km) and the fate of the occupants of the coastal areas critically depends, among other things, on the abrupt rise and fall of sea level. The level of the sea has probably the most fundamental control over sedimentation, not only in the oceans and seas but also, to some degree on land too, in response to both climatic and tectonic factors. The climate is influenced by the growth and decay of ice sheets. The tectonic factor brings about the opening and closing of ocean basins and the sequestering (isolating, separating) of seas.

Erosional and depositional features in different sections of the West and East Indian coast presumably indicate the rise and fall of sea level. This includes features on the west coast of sea cliff, sea caves, drowned valleys, barrier flats and in the east coast, prograding deltas with beach ridges, abrasion platforms,

wave-cut terraces and the like. Herein only a few examples from both coasts and offshore are cited, some of which have also data on the age of the associated features/sediments.

For sometime, the positions of miliolites were taken as a criterion to locate sea levels, as they were considered to be deposits forming close to the coast. These miliolites represent blown sediments over inland and in places, occupy higher altitudes. As such miliolites may not be directly related to higher sea level. The bioclastic shore deposits are more dependable palaeoshore indicators in Saurashtra. However, the occurrences of shelly limestone in Saurashtra at various heights require a tectonic correction before deducing palaeoshorelines.

7 to 8 rows of well defined, broad, symmetrical submerged sand ridges were found on the middle and outer shelf 100-200 km offshore and between 75 and 100 metre depth on the western continental shelf off Bombay (Mumbai). The ridges were more prominent between 85 and 90 metres. These are 0.5 to 10 km wide and 1.5 to 18 m high, several tens of km long, with a few km spacing and trend NNW-SSE parallel to the shelf edge. The sand ridges originated as dunes, which were submerged and reformed into very large sandbars. These are related to Late Pleistocene – Holocene sea level changes.

A rise in sea level and submergence of coastal forests in Kerala were recognised as having taken place during 10,000 – 9000 years B.P. based on ^{14}C dating of the wood and peat deposits in Arabian Sea and cores from inner shelf off Karwar coast. Subsequent to this, a drop in the sea level was noticed during 5000-3000 yrs. B.P. based on ^{14}C ages of lime shell deposits in Vembanad Lake in Kerala. The results of study of pteropods from core samples collected from the shelf off north Kerala suggest that the sea level stood around 100 m below the present mean sea level during the Last Glacial Maximum (~18,000 yrs. ago). A rapid rise in sea level was documented between 15 and 10 Ka B.P. The sea level rise has been slower since 7 Ka B.P.

A Holocene sea level curve was generated for the Western Indian Continental Margin (Fig. 10.19) selecting the areas from Bombay up to around 14° Latitude south, from surface and offshore. The materials dated were littoral concrete, limestone, shell, carbonized wood, peat, ooids, algal limestones etc. Subsequent studies have, however, shown that there has been neotectonic activity in the region (which would naturally give an erroneous picture of some of the sample locations not being *in situ* now) and some of the samples studied earlier could have been not quite reliable for dating purposes (ooids, for instance). Hence the curve as presented here is only tentative and more data is to be collected and plotted for dependable inferences on sea level changes during the Holocene. This curve shows a low at 100 m depth around 14,500 years B.P. and a rise to 0 m depth around 12,000 years B.P. showing a rate of

~10 m/1000 years which was followed by a stillstand for about 2000 years. From 10,000 to 7000 years it rose at a very high rate (~20 m/1000 years). Beyond 7000 years B.P. it showed minor fluctuations. It is not possible to expect imprints of all palaeotopographical features on the sea level curve, since quite a few of them may have been missed during sampling or could have been obliterated during regression of the sea.

On the eastern shelf of India, terraces at -55, -60, -70, -85 and -100 m depths, probably formed during the Late Pleistocene-Holocene transgression.

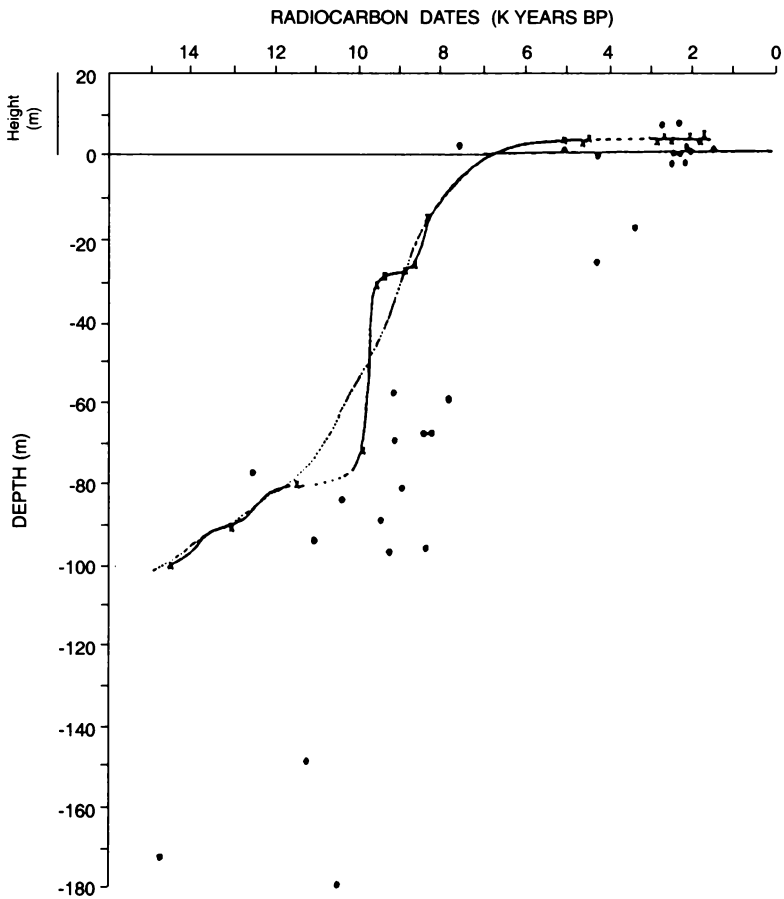


Fig.10.19. Holocene sea level curve for western Indian continental margin relative to present sea level (after Hashimi et al. 1995, p.160).

Algal barriers at –85 and –100 m depths off Visakhapatnam in Andhra Pradesh have been dated 10,790±170 yrs. B.P. and 12,530±170 yrs. B.P. respectively. Over a stretch of 120 km of shoreline of north coastal Andhra Pradesh on either side of Visakhapatnam, a detailed study of all the coastal erosional and

depositional features reveal (Fig.10.20) sea cliffs, sea caves, abrasion platforms and coves. The 'inactive cliffs,' with their toes at about 2 m above msl along the rocky floor/surfaces with sand cover, point to sea level stands of 1.00 to 5.00 metres above the present sea level. A later detailed study at Rishikonda, north of Visakhapatnam, indicated terraces, one of which was associated with tools of Lower Palaeolithic age.

The Pulicat lagoon, north of Chennai (Madras) is underlain by marine sand, silt and clay beds showing middle and late Holocene cycles of desiccation along its western fringe. Within the lagoonal sequence there are bivalve rich layers (^{14}C ages 3100-2320 yrs. B.P.) at depths of 1.10-1.65 m below the surface in the central part. The marine sediments lie over a substrate of marshy peat dated at 6650±110 yrs. B.P. near Sulurpet (4.98 m amsl), 18 km west of the present shoreline. The radiocarbon dates of the peat at Kasireddinelam (1 m a.msl) reveal an age of 4608±122 yrs. B.P., indicating the shift in mangrove line eastwards during the regressive phase. The Late Holocene radiocarbon dates of shells (bivalves) at Attakanitippa and Sriharikota Island are the chain of regressive phases since then. The peat sediment below this shell bed at 9 and 15 m below the mean sea level was perhaps deposited during the transgressive phase. Absence of mangrove pollen in the Late Holocene soil sediments indicates that the sea level fluctuation and climatic conditions during mid- and late Holocene led to the decline in mangrove in the area. Cycles of desiccation and accompanying sea level fall could also account for the development of sand dunes over the western, central and eastern borders of the lagoon, including the Sriharikota spit. Similar studies have been made of sea level fluctuations off the coast of Mahabalipuram (south of Chennai) and off Karaikal, further south, giving comparable results.

In the area around Mandapam, in Ramanathapuram district in Tamil Nadu, a Holocene transgression deep inland is recognised. Along the coast from Cape Comorin (Kanyakumari) to Rameswaram, in the southeastern part of Tamil Nadu, coral colonies and intertidal fossil bearing grainstone, packstone and sandstone beds of Holocene and of a Late Pleistocene high stand are exposed above the present High Tide Level (HTL), at a number of locations. Being a passive margin boundary, free from indications of Late Quaternary seismogenic movements, this sector provides a benchmark for defining minor relative sea level perturbations during the Late Pleistocene and Holocene highstands along a tropical coast lying between latitudes 5°N and 10°N. A series of marine terraces carved on and blanketed by Late Pleistocene biotic and terrigenous accumulations, occur at different elevations (up to 4.4 m) above Low Tide Level at Manappad Point, possibly signifying discrete stillstand episodes, followed by abrupt intervals of rising/falling sea level. The oldest Holocene highstand date recorded by the emerged coral colony at Rameswaram is

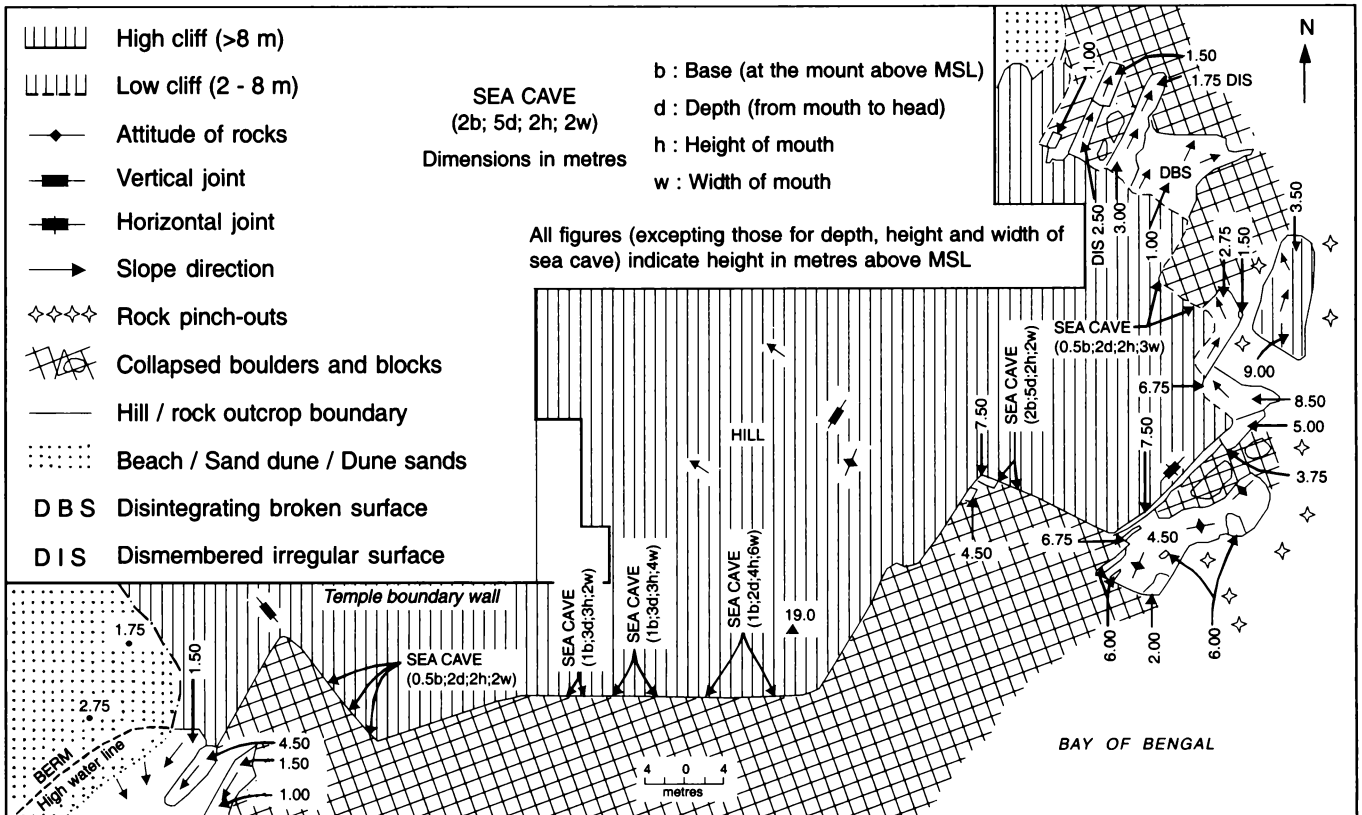


Fig.10.20. Landforms along the seaward margin of the hillock southeast of Reva Polavaram, Visakhapatnam district, Andhra Pradesh (after Prudhvi Raju et al. 1993).

7300 yrs. B.P. It appears that the height of sea level (LTL) during mid-Holocene high stand was around 3 m above the present datum.

Figure 10.21 is a schematic illustration of the relative sea level changes of the east coast of India during Middle to Late Holocene. Most of the data is around Kanyakumari (Cape Comorin), Rameswaram Island and Mandapam, and couple of them from Godavari interdeltaic plain.

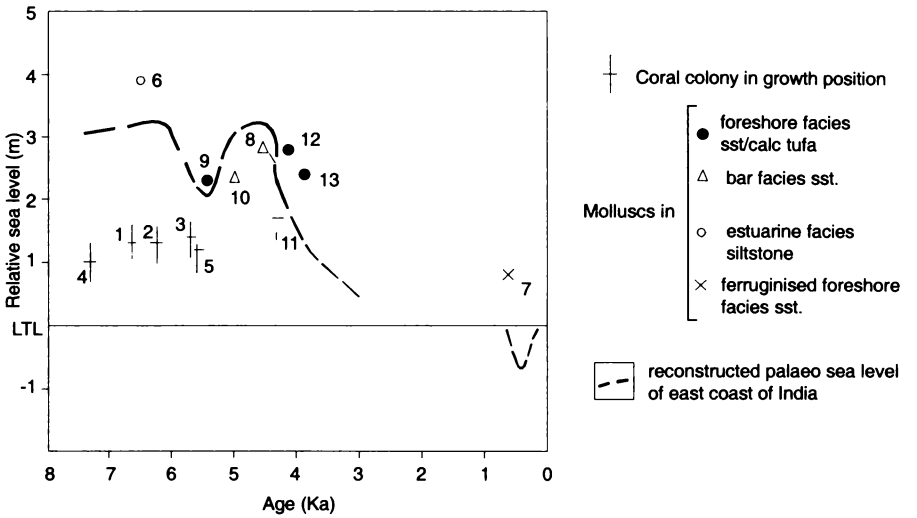


Fig.10.21. Schematic illustration of relative sea level change of the east coast of India during Middle to Late Holocene (after Banerjee, 2000; © 2000; reprinted with permission from Elsevier).

Worldwide studies indicate that the sea level retreated maximum between depths of 121 and 180 m about 18,000 yrs. B.P. during LGM (Last Glacial Maximum). Subsequently the warm period began and the sea level rose to the present one with pauses. A study along the Atlantic Continental Shelf of USA confirms the lowest sea level of the LGM at –130 m. Similarly the oxygen isotope ($\delta^{18}O$) records and ^{14}C dating of deep-sea samples from the Bay of Bengal and Arabian Sea suggest a mean age of the LGM as 18,000 yrs.B.P. with a standard deviation of 1500 yrs. On the basis of oxygen isotope ($\delta^{18}O$) studies, the sea level during the LGM has been estimated to be about –130 m.

Based on the latest information available, the predicted sea level rise for A.D. 2100 ranges from 20 to 85 cm. It can be about 4 m in A.D. 2500, which makes the ensuing inundation scenario grim.

LATERITE

Laterites are a family of rocks, which are the products of intense subaerial

weathering. Laterites occur in many parts of India, but mostly in parts of Peninsular India over all types of rocks, igneous as well as sedimentary. Laterite was reported and named by Francis Hamilton Buchanan from among the rocks in Kerala in 1807. What he named as laterite (meaning a brickstone in Latin) was a weathered material used for building, which was an indurated clay full of cavities and pores, containing a large quantity of iron in the form of red and yellow ochre. Soft when fresh, it can be cut with an axe, and becomes hard on exposure and can be used for construction purposes. There is a National Geological Monument at Angadipuram for laterite in Kerala.

Laterite outcrops form low mounds rising to a few metres above the ground level. When studied in isolation these do not reveal much, as at most places, the profiles are fragmentary and show only two or three units. But a synthesis of data obtained from different locations where in situ alteration in a lateritic profile, say over basalt, is established, the following integrated sequence results in an idealised lateritic profile. Only rarely can one find a section with all the constituents given in the sequence.

The parent rock basalt (C) is followed by weathered basalt, bentonite and kaolinite, these constituting the saprolite and the horizon being rich in silicate (B). This is followed by mottled zone, lithomarge, bauxite, lateritic bauxite, unindurated laterite and duricrust – a horizon rich in oxides (B_{ox}). This sequence is generally termed as laterite. Latosol occurs above these in some places.

Often laterites are found to be associated with planation surfaces. This does not mean that all planation surfaces have a cover of laterite (duricrust) or laterites are formed only if a planation surface is present. But this association is common, not to be missed when extensive planation surfaces are studied in different parts of Peninsular India. It is the exposure of a planation surface for long to subaerial weathering that results in the laterite formation. The laterites are formed simultaneously or subsequent to the formation of planation surfaces. It is generally assumed that the laterite formation takes place when the surfaces were at lower level and it is later that they become plateau surfaces by uplift. Such plateau surfaces are many in Peninsular India.

Rock types of all compositions are affected by laterites. All exposed occurrences, except in Gujarat, occupy tops of different planation surfaces believed to range in age from Cretaceous to Pleistocene. The age of the planation surface need not be identical with the age of the lateritisation. In different parts of India artefacts are seen associated with certain types of laterites, which aid in fixing the age of lateritisation. For example from a study made around east coast of Chennai (Madras) in Tamil Nadu, the association of Acheulian and Mesolithic artefacts on the stable ferricrete surface indicates that the landscape is older than 40,000 to 150,000 yrs. B.P. or even older.

Palaeomagnetic reconstructions of latitudinal position of India during different periods reveal that the Peninsular Indian mass was within the tropical belt during Ordovician and Cambrian times and again between Paleocene and Holocene times. Hence we could expect continuous records of laterites in Indian stratigraphy only during the last 65 million years. High-level laterites have a protracted magnetic history whereas the low-level laterites appear to be mid-late Tertiary in age.

Laterite occurrences in geological columns in India go back at least to Cretaceous age. An exhumed lateritic saprolite is reported at the base of the Himmatnagar (Ahmadnagar) Sandstone of Cretaceous age (?). Laterites of Eocene age in Gujarat, Cambay basin and Cauvery basin are well known. From Miocene onwards laterites occur in many horizons, particularly in Peninsular India.

EARLY MAN IN INDIA

The fossil primates, that have generally formed a small part of the overall vertebrate fossil finds from India, were first discovered from the Siwalik hills, by Falconer and Cautley in the year 1836. Based on the detailed study of all the reported species and finding that there were too many new names for almost the same genera and species, Lewis in 1937 brought them down to four genera and ten species. The four genera named were *Brahmapithecus, Ramapithecus, Sivapithecus* and *Sugrivapithecus*. However, Narmada valley has been one of the areas where since a long time evidence of advent of man and his habitats were unearthed from among the Quaternary sediments followed by in parts of Rajasthan, Himalaya and other parts of Peninsular India.

The discovery of a skullcap of *Homo erectus* from the Quaternary alluvial deposits of Narmada valley in 1982 (Sonakia, 1984) led to intense activity in this region to find further evidences of human ancestry. It is because of simultaneous advances in many fronts, namely on litho-, tephra- and magnetostratigraphy of the region in addition to findings of many new vertebrates that some reasonable estimate could be made of the time of advent of early man in this region. The horizon in which *Homo erectus* was found along with the associated beds and fossils is given in Table 10.19. A Stegodon sp. has been found associated with the hominid skull. This is named as *Stegodon namadicus*. This species shows close affinity to Middle Pleistocene *S. orientalis* of Southeast Asia. Ultimately it is established that Narmada *Homo erectus* is from a bed just above a formation of 0.73 Ka and at least 19 m below a layer of 74,000 yrs. B.P. The human fossil was found on a smoothened erosional platform of the lower conglomerate bed of Surajkhund Formation (*see* Table 10.17).

Homo sapiens from Hathnora was originally identified as *Homo erectus*

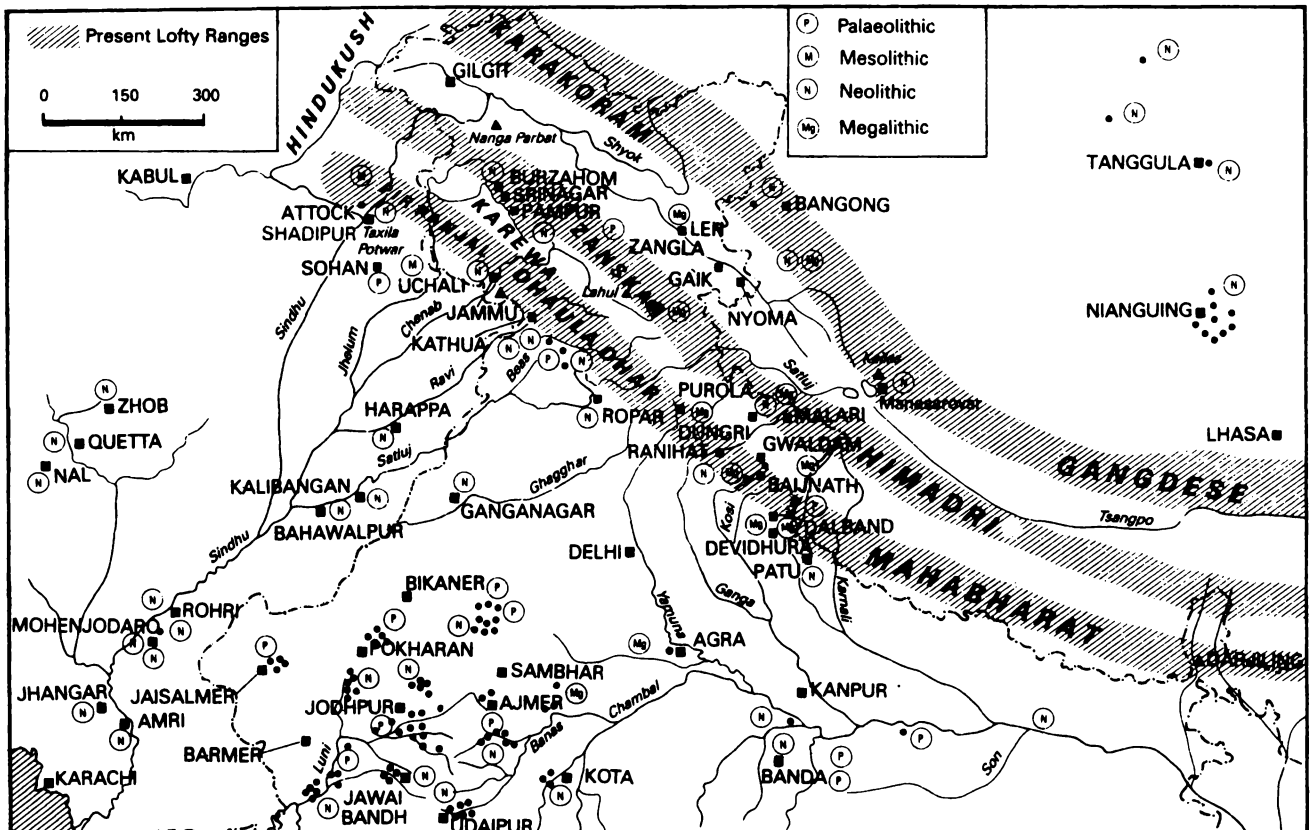


Fig.10.22. Sites of settlements of Stone-Age people in the Himalayan province and neighbouring regions. Solid circles indicate settlements (after Valdiya, 1998, p.129; published with arrangement with Universities Press (India) Private Limited).

narmadaensis. The site Hathnora is situated on the northern bank of the river Narmada about 40 km NE of Hoshangabad in Madhya Pradesh (Fig.10.11). A cemented bouldery pebbly gravel about 0.5 m thick yielded the partial skull of the fossil hominid and a good number of vertebrate fossils comprising proboscideans and bovids. From this unit Late Acheulian Stone Age tools were also collected. The tools are made of Vindhyan Sandstone. The tool kit comprises of amorphous core flakes and scrapers. Considering the archaeological chronology, typo-technological similarities, vertebrate faunal assemblage and geomorphology of the site, a late Middle Pleistocene to early Upper Pleistocene age is assigned to the fossil hominid bearing bed. Anatomically modern representatives of *Homo sapiens* are known from many places in India, such as in Mirzapur and Pratapgarh district, Uttar Pradesh, near Bhopal, Madhya Pradesh, Bhilwara district, Rajasthan and Ahmedabad district, Gujarat.

Majority of the Lower and Middle Palaeolithic sites have been reported from the coarser alluvium of river deposits from parts of Peninsular India. Palaeolithic sites in a primary context have been discovered in rock shelters and open-air situations in the Vindhya Hills to the north of the Narmada valley.

Though in physiographic and geomorphic environments the three regions of Western India, namely Rajasthan, Gujarat and Western Maharashtra contrast with each other, the cultural development in this region appears to be more or less uniform. In north and central Gujarat the base of the microlithic horizon is dated 11±3 Ka, whereas its top is dated 9±1 Ka. This is the first direct dating of the microliths in this region. The presence of microliths and animal bones within the Andhario Timbo dune in Langhnaj, in north Gujarat Plain implies that the microlithic man was present during the last part of the dune accumulation. Presence of swamp deer and rhinoceros along with fish and tortoise suggests that water was available.

Three phases of historic occupation can be distinguished in the Luni basin around Balotra. An Acheulian handaxe found on the surface of a hill near Bajawa village attests to the presence of man in the region during the Lower Palaeolithic times. A gravel, containing flakes, near Karna village has been dated by IRSL (Infrared Simulated Luminescence) to ~80 Ka. A chalcolithic occupation of a gravel surface at Manawara has been dated by the TL method to ~3.4 Ka. This site was covered by a sand dune dated to around 2.9 Ka by GLSL (Green Light Simulated Luminescence) and exposed during the 1979 Luni flood. Some of the settlements in the northern part of India belonging to Palaeolithic, Mesolithic, Neolithic and Megalithic are shown in Fig.10.22.

A few settlements of the Neolithic period are found on top of the Karewa succession in Kashmir. They chose such areas, which have a warm climate, and they have access to other communities nearby like those living in the Potwar

Plains in Pakistan and in the Jammu basin in the south. The fact that the Pir Panjal has now an elevation of 3500-3200 m, seems to indicate that this range may have been uplifted subsequent to the earlier occupation of these parts by the Neolithic man. He must have moved down into the Kashmir valley and was later cut off from the others in the southern plains.

Relatively negligible evidence of very early human settlement in the Ganga Plain is attributed to (i) its being an area of active sedimentation with high rate of deposition and (ii) without any signature of older settlement buried in the alluvial stratigraphy. Large-scale human migration and settlement in the Ganga Plain seems to have begun in Holocene (<10 Ka) where the community transformed from hunter-gatherer to settled agriculturist. The human settlement sites on the surface are generally younger than 5 Ka.

Around Rameswaram, Teri sands (*see* p. 870) contain a rich assemblage of strong human habitation and activity in these areas as early as 8000-9000 years B.P. and as recent as 4000 years B.P.

India is centrally located on the global map of hominid fossils and as such any view on the dispersal or migration of human ancestors bypassing this subcontinent would not be effective. Efforts have been made to find its affinity with Southeast Asian population in Middle Pleistocene time after the hominid exodus from the African continent was initially over. Narmada hominid is indicated to be younger than Indonesian and Chinese *Homo erectus* and as such is not in agreement with the proposed view on Africa as a primary genetic pool for human dispersal.

11

Siwalik Group

INTRODUCTION

The name Siwalik was originally given by Captain P.T.Cautley in the early nineteenth century to the outermost Sub-Himalayan Ranges. He discovered the Siwalik fossils in the course of digging for the Ganga canal near a Shiva (Siva) temple at Haridwar (now in Uttarakhand) in the Ganga Valley. Hence the name Siwalik was given to the sedimentary rocks entombing the fossils. Subsequently it was applied to the mammal-bearing horizon of the Neogene continental deposits of the Himalayan foothills.

Falconer adopted the term in 1835 to designate the nearly continuous series of Tertiary formations stretching from the Indus River in the west to Irrawady River in Myanmar in the east. The succession was later sub-divided three-fold without their actual extent being defined. H.B. Medlicott contributed substantially to our understanding of the stratigraphy of the Siwalik Group, particularly between the Ganga and the Ravi rivers. Besides Pilgrim (1910-1944), who made a very detailed study of the Siwalik vertebrate fauna, others who in the earlier years contributed to our understanding of the sediments of the Siwalik were E.H.Colbert, G.E. Lewis, R. Lydekker and D.N. Wadia.

The Siwalik Group occurs in Potwar basin in NW Pakistan and extends along the Himalayan foothills to Arunachal Pradesh foothills in the SE, except for a small break near Sikkim. The group is about 7 km thick and ranges from Middle Miocene to Early (?) Pleistocene (18.3 to 0.22 Ma) in age. Figure 11.1 shows its extent in Pakistan, Jammu and Kashmir, Himachal Pradesh and Uttarakhand.

The Siwalik Hills are relatively low, and rarely exceed 1000 m above mean sea level with conformable trends running parallel to the Himalaya. The strata are folded and have an outcrop pattern, more or less bounded by a major thrust in the north – the Main Boundary Fault (MBF). The Siwalik is separated from the Indo-Gangetic plain in the south by the Himalayan Frontal

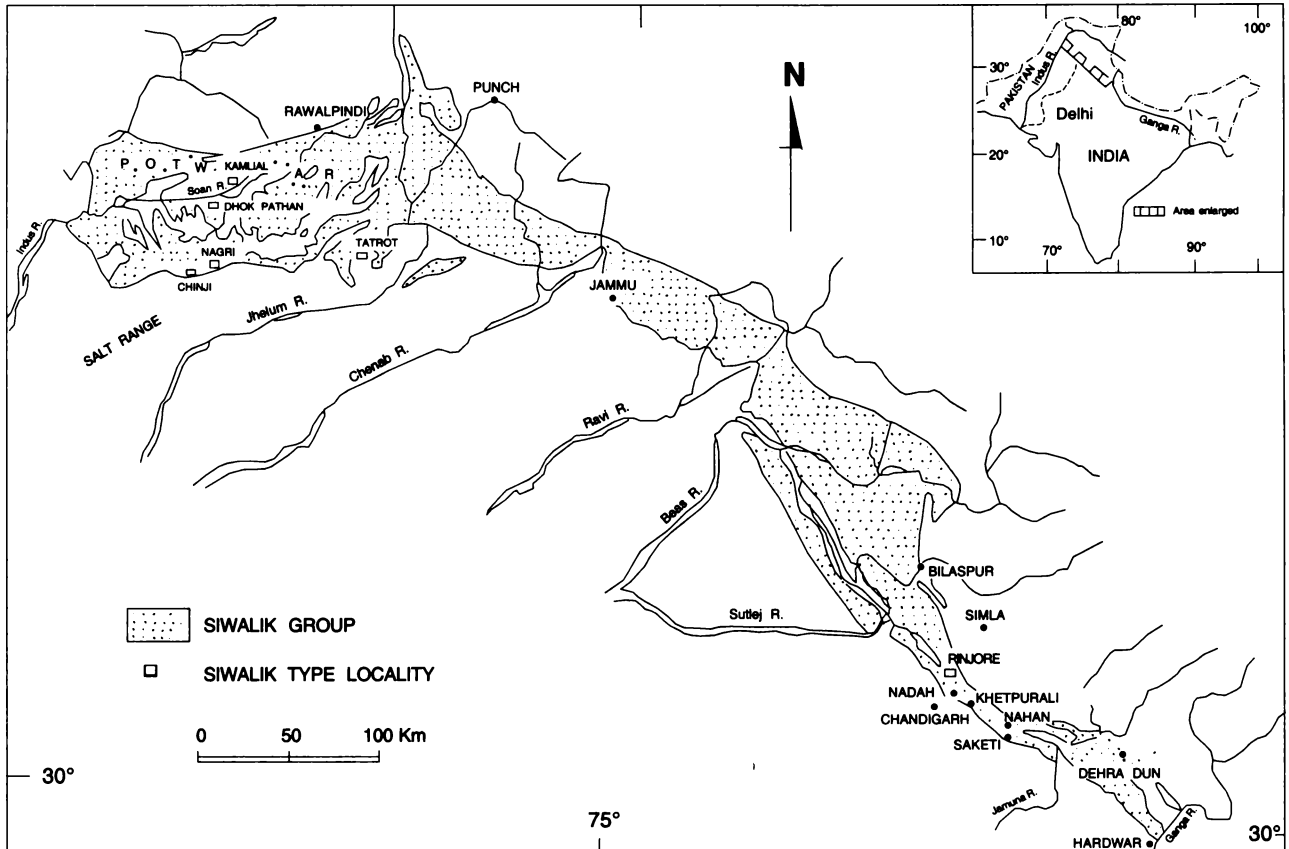


Fig.11.1. Siwalik belt of northwest Himalaya showing important stratigraphic localities (source: Tandon, 1991).

Thrust (HFT). The Siwalik outcrops are generally 10-12 km wide and present themselves as a series of parallel ridges with a steep scarp towards south. Between the outermost hills in the south and the one in the interior in the north are many narrow valleys called "Duns" filled up mostly with Quaternary sediments.

STRATIGRAPHY AND SEDIMENTATION

The high degree of lateral and vertical facies variations and poor continuity of lithological characteristics precludes the possibility of satisfactory lithostratigraphic classification of the Siwalik sediments. Pilgrim, based on his work in Potwar (now in Pakistan), divided the Siwalik into three units, designating them Upper, Middle and Lower based on correlation between Siwalik fauna and similar faunas of Europe. The following is the generally accepted chronostratigraphic division of the Siwalik Group (Table 11.1).

According to Pilgrim, the various stages (as termed by him) are characterised by definite vertebrate fossil assemblages. However, the fossil horizons are highly restricted, the lithology showing considerable lateral variations. The Siwalik Group has been grouped into Lower, Middle and Upper divisions

Table 11.1. Chronostratigraphic division of the Siwalik Group (source: Tandon et al. 1988)

Geological Time Scale		Classification of the Siwalik Group	Standard European Equivalent	Age calculated from reversal stratigraphy	Continental Equivalent
Pleistocene	Upper Siwalik	Boulder conglomerate	Cromerian	1.5 to 0.5 m.y.	?
		Pinjor	Villafranchian	2.47 m.y.	Mid.-Late Villafranchian
		Tatrot	Astian	5.5 m.y.	Ruscinian-Early Villafranchian
Pliocene	Middle Siwalik	Dhok Pathan	Pontian	8.5 m.y.	Turolian L. Vellesian
		Nagri	Sarmatian	10.8 m.y.	E. Turolian
	Lower Siwalik	Chinji	Tortonian	14.3 m.y.	Oeningian-Vellesian
Miocene		Kamlial	Helvetian		
				18.3 m.y.	Pre-Oeningian
		Muree Group	Burdigalian		

Table 11.2. Lithostratigraphy of the Siwalik Group (after Karunakaran and Ranga Rao, 1976)

Subgroup	Lithology	~Thickness
Upper Siwalik	B. Predominantly massive conglomerate with red and orange clay as matrix and minor sandstone and earth buff and brown claystone A. Sandstone, clay and conglomerate alternation	2300 m
Middle Siwalik	B. Massive sandstone with minor conglomerate and local variegated claystone A. Predominantly medium to coarse-grained sandstone and red clays alternation, soft pebbly with subordinate claystone, locally thick prism of conglomerate	1400 m to 2000 m
Lower Siwalik	B. Alternation of fine to medium-grained sporadically pebbly sandstone, calcareous cement and prominent chocolate and maroon claystone in the middle part A. Red and mauve claystone with intercalations of medium to fine-grained sandstone.	1600 m

based on gross lithology and superposition, as observed in the field, over considerable area and is presented in Table 11.2.

The entire molasse phase of the Lower Siwalik is chiefly a multi-storeyed, multilateral fluvial complex, primarily of channel lag and of lateral accretion deposits. The mineralogical composition of the grains reflects denudation of a stratigraphically normal metasedimentary terrain of the crystalline thrust sheet, yielding metamorphic detritus. Though sedimentary detritus is present, it decreases considerably upwards in the molasse sequence.

The Middle Siwalik strata consist of sandstone bodies with interbedded siltstone and shale, followed by mudstone, marl and finally pebbly sandstone and sandy conglomerate. These are indicative of flood plain deposits. The calcareous content in a part of the sequence has been derived from clasts of the Tertiary limestones of the Himalayan source.

The Upper Siwalik sediments were deposited under two distinct conditions, one as inner Siwalik valley fillings and the other as regular river channel and flood plain deposit, to the south of the present Siwalik Ranges. This is probably the result of the uplift of the inner sector of the Neogene basin towards the end of the Zanclian time (Early Pliocene). An examination of the sedimentary history along a section in Kangra sub-basin in Himachal Pradesh, based on magnetic polarity studies, revealed episodic increasing and decreasing rate of sediment accumulation ranging from 19 cm/1000 years to 50 cm/1000 years.

The Siwalik sediments have been deposited broadly in four environments. These are (i) piedmont, (ii) outwash plains, (iii) channel and flood plains and (iv) lacustrine, which shifted in space and time during the deposition of an enormous thickness of molassic sediments between 5000 and 6000 m, preserving a unique record of Himalayan tectonic events.

It was believed that the drainage during part of the Tertiary and the Siwalik times in the Indo-Gangetic depression had but one outlet, where the Indus now runs into the sea; that this great river system drained the whole of the Himalayan region. It was called Indo-Brahm River by Pascoe and Siwalik River by Pilgrim. Though based on faunal evidence this hypothesis was challenged but recent geophysical studies of the bottom configurations of the Indo-Gangetic Plain again seem to suggest the possible existence of a major river during the later Siwalik times flowing due west from the east.

FAUNA FROM SIWALIK

The Siwalik Group is well known for its wealth of vertebrate fauna, though they are confined to only certain horizons and only some of them are of biostratigraphic importance. Of added significance is the occurrence of hominoids in almost all the formations.

The following list of fauna is selected from among those reported from the different formations (Prasad, 2001). In Plate 11.1 is presented sketches of what some of the fauna might have looked like.

Lower Siwalik

Carnivora	:	*Amphicyon* sp., *Viverra chinjiensis*
Proboscidea	:	*Deinotherium, Gomphotherium, Stegolophodon*
Suidae	:	*Listriodon, Conohys* sp.
Anthracotheriidae	:	*Hemimeryx, Telmatodon*
Rhinocerotidea	:	*Aceratherium, Chilotherium*
Giraffidae	:	*Propalaeomeryx*
Bovidae	:	*Dorcadoxa*
Rodentia	:	*Rhizomys, Copemys*
Primates	:	*Sivapithecus, Sugrivapithecus*

Middle Siwalik

Carnivora	:	*Sivanasua, Crocuta, Lycyaena*
Proboscidea	:	*Deinotherium*
Equidae	:	*Hipparion antelopinum*
Suidae	:	*Tetraconodon, Propotamochoerus* sp.
Anthracotheriidae	:	*Anthracodon, Anthracotherium*
Rhinocerotidae	:	*Brachypotherium, Gaindatherium*
Giraffidae	:	*Vishnutherium, Giraffokeryx, Hydaspitherium*
Bovidae	:	*Gazella, Protragocerus*
Rodentia	:	*Rhizomys, Kanisamys*
Primates	:	*Ramapithecus*

Upper Siwalik

Carnivora	:	*Crocuta, Agriotherium, Felis*
Proboscidea	:	*Trilophodon, Paratetralophodon, Stegodon*
Equidae	:	*Cormohipparion, Equus sivalensis*
Suidae	:	*Hippohyus, Sus, Dicoryphochoerus*
Anthracotheriidae	:	*Choeromeryx, Hippopotamus, Cervus*
Rhinocerotidae	:	*Rhinoceros, Coelodonta*
Giraffidae	:	*Sivatherium, Camelopardalis*
Bovidae	:	*Tragocerus, Bos, Bison*
Rodentia	:	*Rhizomys, Hystrix, Nesokia*
Primates	:	*Gigantopithecus, Papio*

(Extracted from Prasad, 2001, pp.20-21)

A brief description of the distribution of sediments of Siwalik Group in some of the States is given below:

Jammu and Kashmir

The Siwalik sediments overlie the Murree in this sector of Kashmir Himalaya. Complete development of Siwalik can be seen in the Jammu Hills, where they attain a thickness of about 6000 m with an outcrop width of about 40 km as seen along the Chenab section in Riasi-Aknoor sector and in Ramnagar-Samba sector.

Lower Siwalik: These occur in Poonch-Mirpur region and consist of hard red sandstone, grey buff and red shales, very hard red clays and calcareous sandstone, at places pebbly in the lower part and bright red shales and sandstones in the upper part. The rocks are rich in mammalian fossils belonging to Carnivora, Proboscidea and Primates and the families of Suidae, Equidae and Giraffidae. These are part of Kamlial and Chinji Formations.

Trace fossils are found in the Lower Siwalik rocks at Mansar and Jhajjar Kotli in Jammu region. The siltstones are bioturbated with branched burrows and resting traces along with semicircular and circular imbricate structures.

Middle Siwalik: The Chinji Member of the Lower Siwalik grades into the Helan Member of the Middle Siwalik in Poonch region. It consists of massive, soft coarse sandstone, with subordinate clays and shales underlain by a rather prominent zone of deep red calcareous shales and nodular clays. They attain a thickness of about 500 m. Several of the giraffe family and the short-jawed proboscidean *Synconolophus* are confined to this formation while Bovidae made their first appearance.

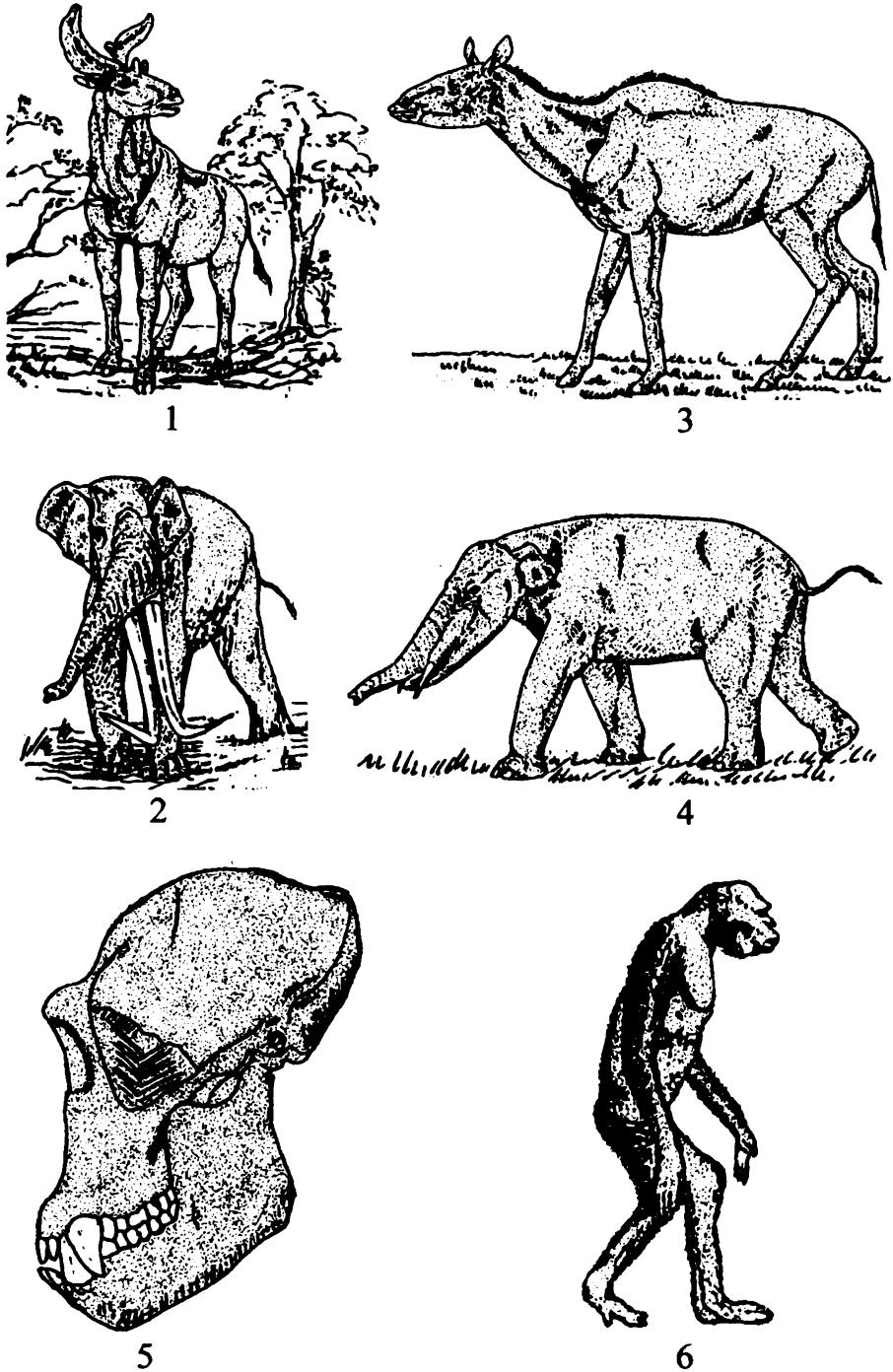


Plate 11.1. 1. Sivatherium, giraffe, shoulder height about 200 cm (Upper Siwalik). **2.** *Stegodon* (Middle to Upper Siwalik). **3.** *Helladotherium*, extinct giraffe (Middle Siwalik). **4.** *Gomphotherium*, shoulder height over 2.5 m (Lower Siwalik). **5.** Chimpanzee, Lower skull, non-human primate (Siwalik). **6.** *Ramapithecus*, an extinct man-like ape showing characters of a hominid (Middle Siwalik, now synonym of *Sivapithecus*) (Courtesy: A.C. Nanda).

Upper Siwalik: These have a very large thickness, consisting of red earthy clays with massive beds of coarse pebbly sandstone, gritty in the lower part, and overlain by about 1000 m thick boulder conglomerate, a true boulder conglomerate grading to that of a gravelly conglomerate. The Upper Siwalik of Jammu region is divided into Parmandal, Nagrota and Boulder Conglomerate Formations. Their lithological variations and characteristic fauna are presented in Fig.11.2.

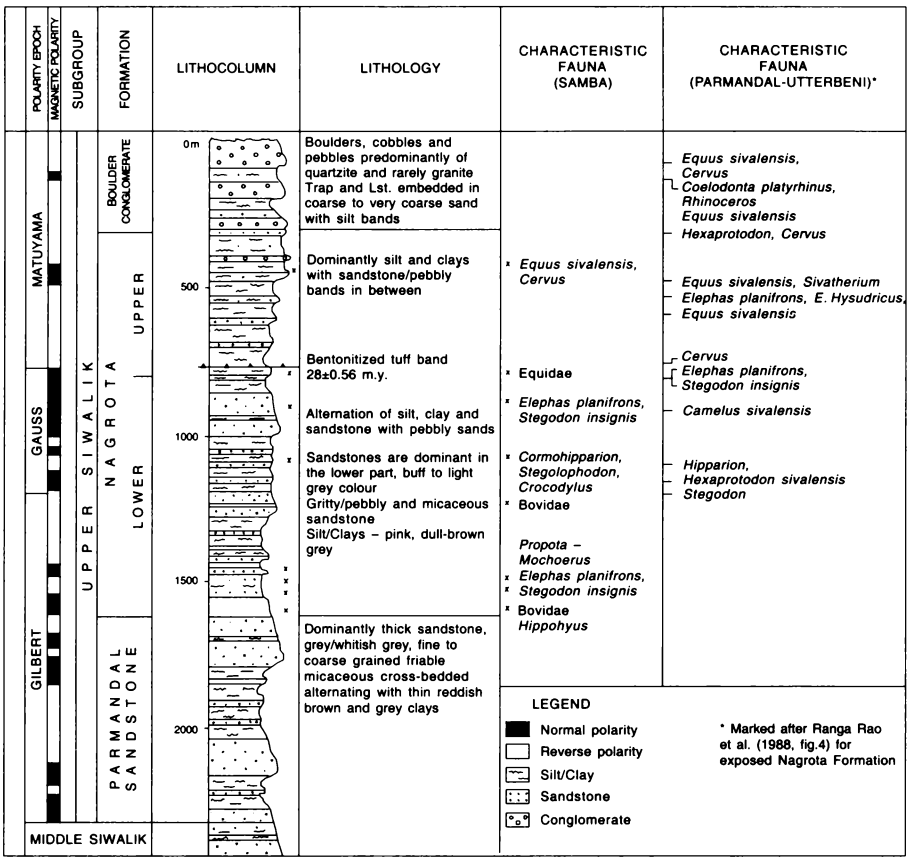


Fig.11.2. Stratigraphy and mammalian fauna of the Upper Siwalik of the Jammu region (source: Nanda, 1997).

Himachal Pradesh

The Siwalik Group in Himachal Himalaya forms a parallel foothill belt along the southern margin of the Paleogene Sirmur belt between the Ravi and the Yamuna rivers (Fig.11.3). In the Punjab re-entrant, it has a maximum width of about 100 km between Hoshiarpur and Jogindarnagar. The Siwalik sediments generally overlie the Dharamsala Group (having two formations Dagshai and

Kasauli). A gradual transition from Kasauli to Lower Siwalik (Nahan) is seen. However, at Dharamsala, Sarkaghat and Nalagarh the Siwalik Group directly overlies the Sirmur Group. At Haritalyangar near Bilaspur, the Lower Siwalik rests on Dagshai with a profound unconformity, indicating a period of earth movements.

Detailed studies on the heavy mineral content and fossils present in the Himachal Siwalik give a clue to the nature of the sedimentary provenance.

Lower Siwalik: The heavy mineral assemblage consists of various opaques, garnet, tourmaline, epidote, staurolite, zoisite, zircon, rutile and chlorite. Epidote and staurolite are uniformly present in the sediments. The Lower Siwalik has yielded a rich mammalian fauna in the area around Nurpur along with a few reptilian remains and shells of *Unio*. The Lower Siwalik sediments are characterised by the preponderance of angiosperm pollen over pteridophytic spores and gymnospermous pollen.

Middle Siwalik: Petrologically, the lower boundary of the Middle Siwalik coincides with the influx of kyanite in the heavy mineral assemblage. Moderately rich assemblage of opaques, garnet, tourmaline, epidote, staurolite, zoisite, zircon, rutile, chlorite and kyanite with sporadic sphene occur. The appearance of kyanite marker attended by lithological changes in the Siwalik points to a major change in depositional pattern, accompanied by earth movements resulting in the unroofing of extensive kyanite bearing crystalline thrust sheets in the area, north of the Siwalik basin.

A rich collection from Haritalyangar also includes faunal groups of Rodentia, Carnivora, Perissodactyla, Artiodactyla and Proboscidea. An insectivora *Siwalikosorex prasadi* was also found.

The recovery of *Ramapithec*us (Plate 11.1 - 6), an hominid, from the Middle Siwalik, is of great significance as this is one of the forerunners of early man. The fossil remains of *Ramapithecus* show that they had typical hominid teeth with cusps splayed apart as in man, small incisors, and practically no canine and small vertically emplaced incisors. The upper teeth were arranged in a parabolic arch similar to that in man and with two sides of the jaw united without a simian shelf. It is the earliest known hominid. The occurrence of many advanced apes and *Ramapithecus*, according to some, clearly indicates, that the Siwalik of India formed the radiative centre for the evolution of apes and man. *Ramapithecus* was a tool user and fashioned stone implements, though crude, and effectively used these tools for hunting small games such as deer and rabbits. Siwalik have also yielded fossils of *Gigantopithecus*, man-like ape, which stood about 180 cm and possessed massive jaw and teeth. It was a massive herbivorous species larger than gorilla, not arboreal and essentially a

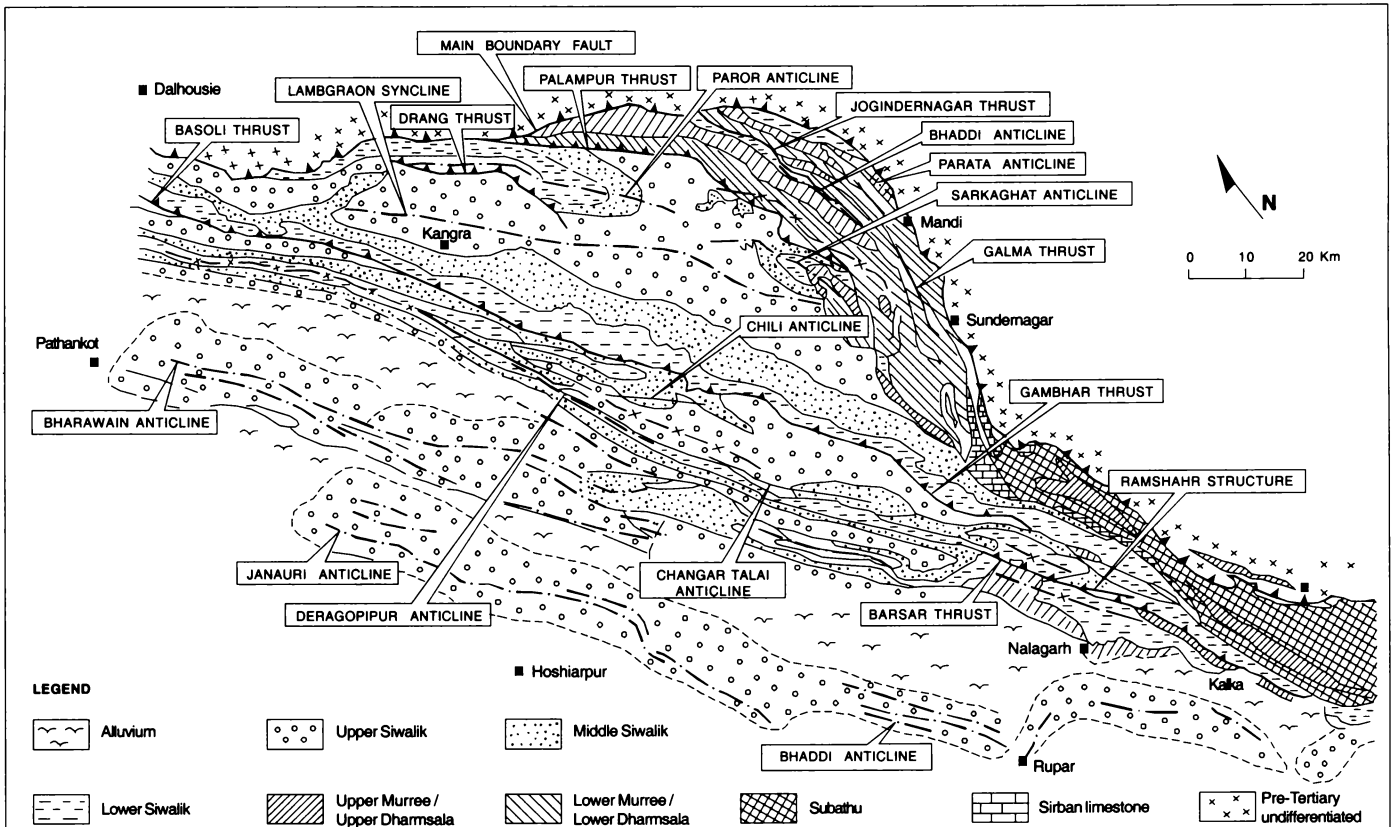


Fig.11.3. Distribution of the Siwalik Group and older Cenozoic rocks in the zone of the Punjab re-entrant and adjoining areas (after Karunakaran and Ranga Rao, 1976).

dweller in open forest. Several fossils of *Ramapithecus* and *Sivapithecus* have been discovered not only from Himachal Pradesh but also from Punjab and Kashmir.

The interpolated ages for the specimens of *Ramapithecus punjabicus* range from 7.0 to 7.5 Ma. The holotype of *Gigantopithecus bilaspuriensis* occurs in chron 6 of MPTS (Magnetic Polarity Time Scale) and has approximate age of 6.3 Ma.

The chief palynological characteristic of the Middle Siwalik sediments is the dominance of gymnospermous pollen over angiospermous pollen.

Upper Siwalik: The conglomeratic facies of the Upper Siwalik is found in the Mandi re-entrant, mainly in the Lambagraon syncline and in the area immediately to the southeast of the main tectonic divide between the Siwalik belt and the older Sirmur belt.

The Upper Siwalik is characterised by a very complex suite of heavy minerals including hornblende, sillimanite and andalusite indicating a derivation in part from the advancing crystalline thrust sheet from the north. The Upper Siwalik has yielded the following faunal assemblages in the outermost Siwalik Range between the Yamuna and Sutlej Rivers: *Stegodon ganesa* (Plate 11.1- 2), *S. insignis, Hypselephas (*now included in *Elephas), Equus sivalensis, Hexaprotodon* sp., *Rhinoceras platyrhinus, Proamphibos kashmiricus, Merycopotamus* sp., *Leptobos* sp., *Hippopotamus* sp. There were a few fossil reptiles also. The fishes collected from the Pliocene beds of Ladhyani (Haritalyangar) in Himachal Pradesh indicate that this fluvial community has been stable from the Pliocene up to Recent (Holocene) times.

Fossil remains of *Mus* sp. (fossil mouse, Rodentia) were recovered from the Tatrot Formation (Late Pliocene) in Saketi.

A complete tusk and molars of *Stegodon ganesa* collected from Nagrota Upper Siwalik (10 km NW of Jammu) by Wadia brought this area to light for the first time. In the Siwalik, the genus *Stegodon* ranges from Dhok Pathan to Pinjor Formations. The genus is also distributed widely in Java, China and Myanmar during the Pleistocene.

Uttarakhand

Siwalik Group here extends for over 250 km and is 25 km wide, but much less than those in Himachal Pradesh. Kalagarh, one of the principal areas investigated, yielded hominid and other vertebrate fossils. The formations and the lithological constituents are given in Table 11.3. Total thickness is about 4500 m here.

In Uttarakhand, between Laldhang and Kotdwara, the Lower Siwalik is

Table 11.3. Generalised Siwalik stratigraphy in Uttarakhand (source: Ranga Rao et al. 1981)

	Formation/Beds	Lithology
Upper Siwalik	Danaur Boulder Bed	Sandstone boulders with thin red earth clays.
	Quartzite pebble conglomerate	Quartzite pebble conglomerate with orange brown sands and brown earthy clays
Middle Siwalik	Am Sandstone	Predominantly medium-grained sandstone with calcareous concretions and pebbles
	Budir Formation	Alternations of medium-grained sandstone and clay/shale
Lower Siwalik	Siroli Formation	Fine to medium-grained sandstone with reddish brown marly clays
	Nandhaur Sandstone	Predominantly fine-grained sandstone with lenticles of lignite
	Kalounia Red Clay	Red clay
	Chenadhaki Formation	Alternations of green claystones and hard sandstones with calcareous concretions
	Paurjia Purple Clay	Purple and maroon clay with thin, fine-grained sandstone

dominantly arenaceous. Clays, however, appear in Ramganga-Palain river sections. Middle Siwalik is best exposed south of Dehra Dun in the Mohand section in the core of Mohand anticline (Fig.11.4), where it attains a thickness of about 1800 m. It is predominantly made up of multi-storied sandstone. There are many facies changes (Fig. 11.5) and a variety of sedimentary structures are met with.

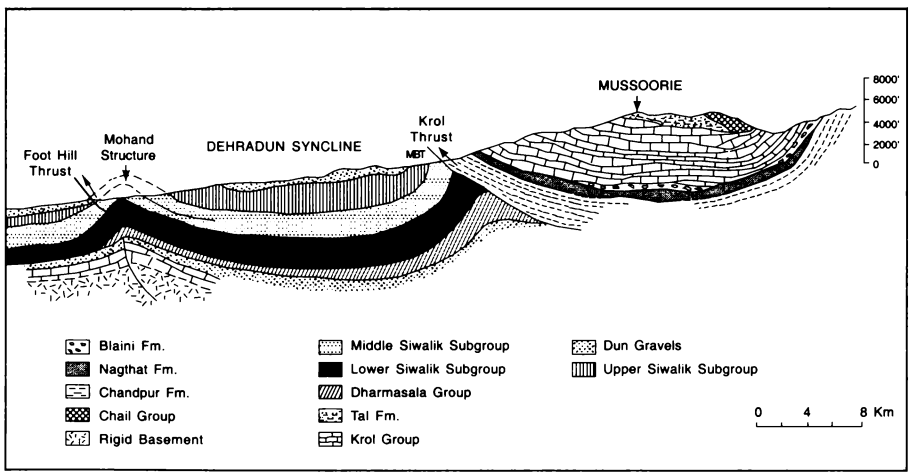


Fig.11.4. Geological cross-section across Mohand and Mussoorie area (compiled from Rao et al. 1974 and Shankar, 1975). (source: Tandon et al. 1988, p.10).

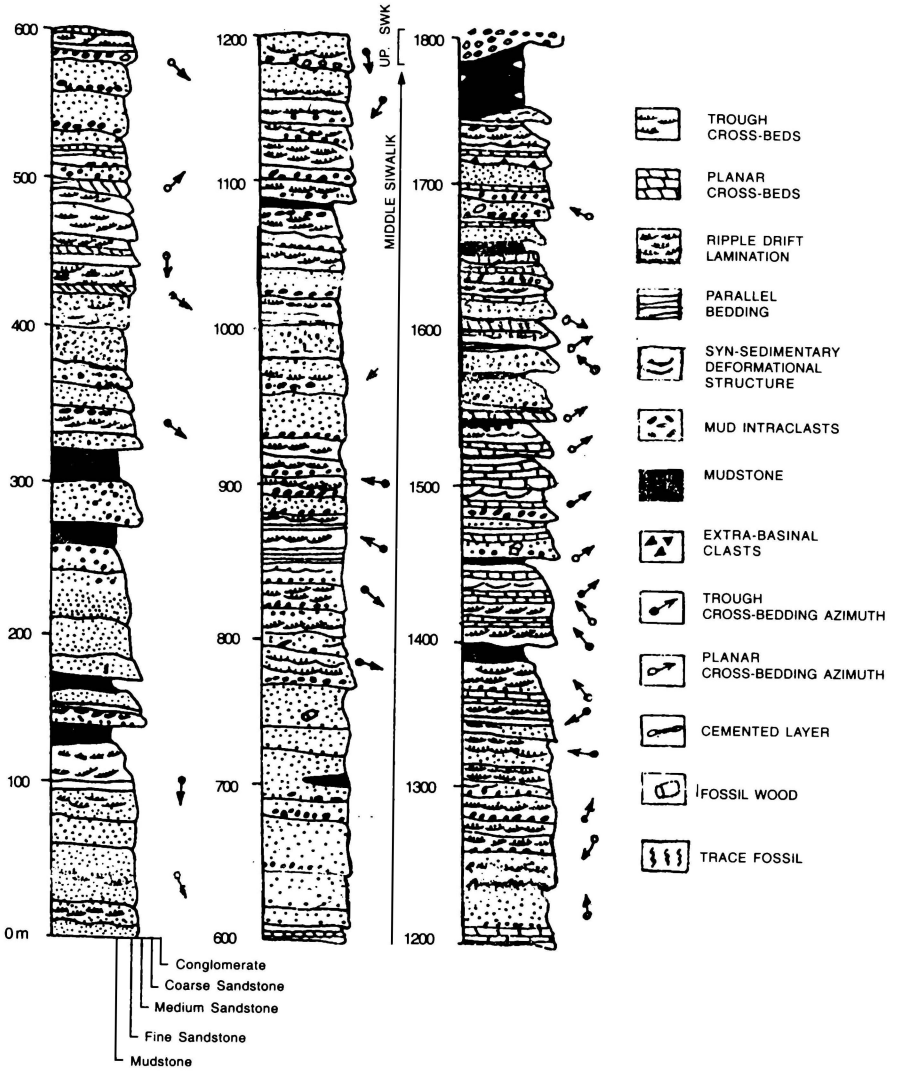


Fig.11.5. Lithological column through a sequence of multistoried sandstones of the Middle Siwalik Subgroup in the Dehra Dun region (source: Tandon, 1991, p.186).

The Siwalik Group of rocks (sandstones and siltstones) exposed near Kalagarh basin (Pauri, Garhwal) are more than 600 m thick. In addition to piscean and reptilian remains, other groups include *Sivapithecus*, *Ramapithecus,* Hominoids (Primates), *Viverra* (Carnivora), *Deinotherium* (Proboscidea), *Hipparion* (Equids), *Giraffokeryx* (Giraffid) and *Dorcadoxa* (Bovid).

West Bengal

In the Terai region of the northern part of Jalpaiguri and Darjeeling districts

of West Bengal, the sandstone is usually soft and friable but close to the thrust, it is highly indurated and sheared. In the upper pebbly horizon, pebbles mostly made up of quartzite, jasper and rarely of phyllite are present. Besides these, lenses of lignite and fossil wood commonly occur in the Siwalik.

Arunachal Pradesh

The Siwalik Group occurs as a linear belt all along the foothills from the border with Bhutan in the west, to Roing in the Dibang Valley in the east where it ends against the Roing fault. Its northern limit is defined by the Main Boundary Fault separating it from the pre-Tertiary sequence, while in south the Brahmaputra alluvium defines its boundary, which at places appears to be tectonic (Foothill fault). The sediments have been divided into Dafla, Subansiri and Kimin Formations.

TREND OF LIFE IN SIWALIK

The end of Pliocene was marked by the commencement of arid conditions, which resulted in the complete eradication of *Dipterocarpus* from northern India. The discovery of *Pinus* from the Middle Siwalik sediments supports the hypothesis, that by this time, the Himalayan ranges had attained an elevation ranging from 400 to about 1500 m. The flora consists of about 55% angiosperms. The families Dipterocarpaceae, Gramineae, Polypoiaceae and Cyperaceae were widespread throughout the subcontinent.

The fauna changed radically from the Chinji (very Late Miocene – Messinian) and primitive forms were replaced by more advanced ones in the Nagri Stage (Zanclean – Early Pliocene). By the beginning of Dhok Pathan (Piacenzian-Late Pliocene), there was a marked increase in the steppe grassland genera including abundant hipparions, papionids, bovids and giraffoides. The proboscidians were greatly diversified and there was increase in the taxonomic diversity of carnivores. The appearance of the first hippopotamids, antelopes and cervids occurred at the end of Nagri Formation. In contrast to the warm, moist, tropical rain-forested areas of low relief that were predominant during the Kamlial and Chinji times, the Dhok Pathan time indicates an open country habitat with cold climate, while the climate of the Nagri Formation is intermediate between those of Chinji and Dhok Pathan.

Recent studies reveal that the lithological boundaries in different sections of the Siwalik are time transgressive. Fauna considered to belong to Lower Siwalik in some sections, are found to occur in Middle Siwaliks somewhere else. Typical strata considered to be almost a horizon marker, also turn out in higher or later horizons in adjoining areas. For example, red beds (mainly

mudstones), which are considered characteristic of Lower Siwalik, yield typical Chinji fauna in Ramnagar, Jammu whereas the same red bed succession about 120 km east of Ramnagar yielded Middle Siwalik fauna. Even in Kalagarh, Uttarakhand the red beds are time transgressive and yielded both Lower and Middle Siwalik elements including hipparionines. Similarly multi-layered soft, grey, medium-grained sandstone bodies are characteristic of the Middle Siwalik. These sandstone bodies near Paonta yielded typical Pinjor fauna, which includes *Equus* and *Cervus.*

The Haritalyangar fauna contains type specimens of several hominoid primates, which are assigned a new last appearance datum age based on a magnetic polarity stratigraphy. The youngest assigned age for *Sivapithecus indicus, S. sivalensis* and *Ramapithecus punjabicus* in Asia is about 7.0 to 7.5 Ma. The age of the holotype specimen of *Gigantopithecus bilaspurensis* is about 6.3 Ma. The Nahan Sandstone Formation (Lower Siwalik) is at least in part contemporary with the Nagri Formation (lithofacies) of the Potwar Plateau, Pakistan.

Using magnetostratigraphy, the upper and lower limits of a few biostratigraphic interval-zones have also been arrived at:

Elephus planiformis	Interval-Zone	2.9 to 1.5 Ma
Hexaprotodon sivalensis	Interval-Zone	5.3 to 2.9 Ma
Selenoportex lydekkeri	Interval-Zone	7.4 to 5.3 Ma
Hipparion sp.	Interval-Zone	9.5 to 7.4 Ma

These zones were identified by American workers on the basis of first and last appearance of various taxa, their relative abundance and extinction in Pakistan. This may not be entirely applicable to the whole of Siwalik Group. For the Upper Siwalik, the modified new interval zones were recognised as under:

Equus sivalensis	Interval-Zone	2.6 to 0.6 Ma
Elephus planiformis	Interval-Zone	3.6 to 2.6 Ma

The vertebrate fauna of Mesozoic and Early Cenozoic ages of India show close affinity to the Laurasian and Tethyan elements than to the Gondwana, supporting the view that mammals from the northwest were the first to invade the Peninsular India. The change from Tatrot fauna to Pinjor fauna was found to occur at 2.58 Ma (Gauss/Matuyama boundary), based on the simultaneous occurrence of *Equus, Elephas, Bos* and Cervid with antlers. Transition from Pliocene to Pleistocene in the Siwalik foothills is represented by a nearly continuous sedimentary sequence involving the Tatrot and Pinjor Stages.

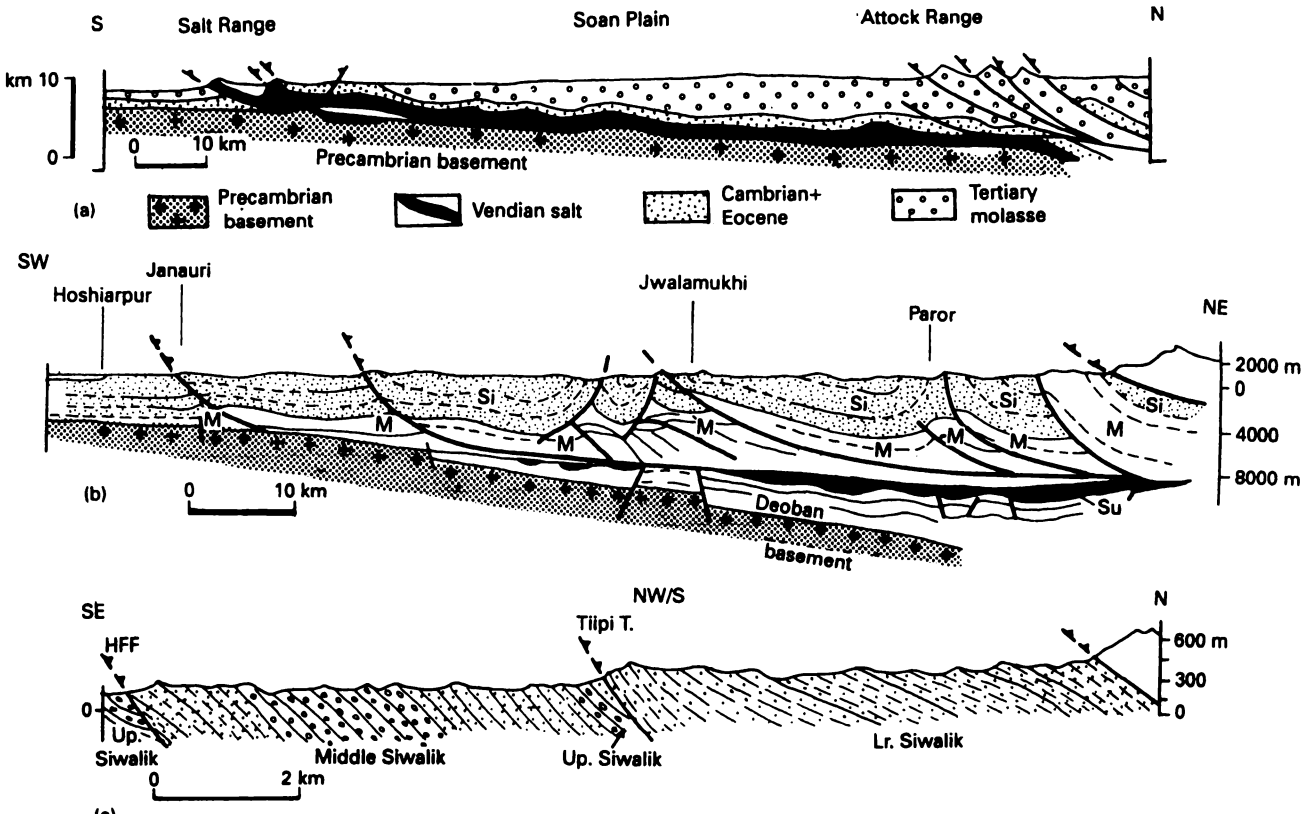


Fig.11.6. Structural architecture of the Siwalik terrane. (**a**) In Pakistan, after R.J. Lillie et al. 1987. (**b**) In Panjab after V. Raiverman et al. (1993). (**c**) In Arunachal after C. Karunakaran and A. Ranga Rao (1976). [Si = Siwalik, M = Muree, HFF = Himalayan Frontal Fault] (source: Valdiya, 1998, p.96; published with arrangement with Universities Press Private Ltd.).

TECTONIC SETTING AND STRUCTURE

The Himalayan collisional orogenic belt represents a complex zone of uplift, which is composed of at least five lithotectonic provinces from the north as follows: (i) Indus Suture Zone, (ii) Tibetan Tethyan Zone, (iii) Higher Himalaya, (iv) Lesser Himalaya and (v) Sub-Himalaya, Siwalik mainly forming the Sub-Himalaya. The foothills are asymmetric showing steep faces (scarps) towards the southern floodplains with gentle slopes towards the north.

Siwalik basin is an important constituent of the Himalayan foreland. It developed ~20 Ma ago and has collected sediments from the uplifted terrane(s) of the Himalayan orogenic belt. It is considered to be a part of a linked sedimentary system - Himalayan uplifts – Siwalik basin (molasses) – deltaic (Ganga-Brahmaputra) – submarine fan (Bengal-Nicobar fan) system. These sediments are shed from orogenic highlands formed by continental collision and pour longitudinally through deltaic complexes into remnant ocean basins.

In this larger framework, Siwalik basin is but one element in the stages of evolution of the Himalayan Foreland. It has a cause–effect relationship with the Himalayan orogenic processes. The study of the effect (Siwalik basin and its fills) provides information on the nature and timing of the thrust, fold and uplift events in the orogen, the nature, timing and relationship of interactive basinal and source terrane tectonics.

Main Central Thrust (MCT) separates the Lesser Himalaya from the Higher Himalaya and the Himalayan Frontal Thrust (HFT) separates the Sub-Himalaya from the Indo-Gangetic Plain in the south. The continued movements and uplifts in the frontal areas of the Himalayan orogen resulted in the shifting of the depositional sites basinwards, and therefore successively older parts of the Siwalik column are overlapped by younger coarser deposits.

The large thickness of the Siwalik stratigraphic column cannot be explained without involving basinal subsidence. The general pattern of cyclicity is suggestive of an apparent balance between basinal subsidence and fluvial aggradation. Basinal subsidence, repetition of cycles and the rate of underthrusting of the Indian plate have been related to the Siwalik depositional megacycles.

Structurally, the Siwalik has been folded and overthrust to the south by the Lower Cenozoic formations, which in turn are thrust over by the pre-Cenozoic (Fig.11.6). Within the Siwalik basin itself, thrusting has brought about a frequent reversal of the stratigraphic sequence. The intensity of thrusting decreases from northeast to southwest, where the Siwalik is characterised by open folds dissected by high angle reverse faults, hading north. In some areas closely spaced thrusts have resulted in the development of schuppen structures. The fold-fault pattern that has resulted from the overall structural evolution is

one of synclinal valleys and anticlinal ridges separated by thrust planes. Broadly, they may be divided into three tectonic zones, namely the Outer zone showing open folds, the Middle zone of open folds and monoclines intercepted by north-hading reverse faults, and the Inner zone of closely spaced compressed folds and faults lying close to the Main Boundary Fault.

CORRELATION AND AGE

In Pakistan, lithostratigraphy of the Siwalik Group was standardised by a Stratigraphic Committee, though it is not accepted by all. American workers were the first to carry out combined vertebrate palaeontological and magneto-stratigraphic studies in Potwar Plateau and these studies now form the base for dating various horizons, first and last appearance of the various Siwalik taxa and for the recognition of the biostratigraphic zones.

Falconer dated Siwalik as Miocene, and Lydekkar as Pliocene. It was Pilgrim, who divided them, based on his work in Potwar (now in Pakistan), into three units designating them Upper (Upper Pliocene – Lower Pleistocene), Middle (Lower Pliocene) and Lower (Middle Miocene), using correlation between Siwalik fauna and similar faunas of Europe.

In view of the non-applicability of the use of fauna for regional correlation, an attempt was made to use heavy minerals and grain size variations in the sediments to subdivide the sequences and what is termed as "energy sequences" suggested.

Palaeomagnetic dating has now provided a firm basis for correlation of the Siwalik beds with the Standard Magnetic Polarity Time Scale (MPTS). According to MPTS, the Pleistocene epoch commences at the top of the Olduvai event, which has been dated at 1.8 Ma ago.

The Siwalik Group has been investigated for magnetostratigraphy in several sections of the foothill belt of Himalaya, both in Pakistan and India and a number of dates have been arrived at indicating a range for the formation of certain deposits. Based on the various dates obtained a tentative range of ages for the different formations of this group is presented in Table 11.1. The Tatrot-Pinjor faunal break is considered to have taken place around 2.58 Ma.

12

Geology of Offshore Basins

INTRODUCTION

Though some detailed studies had been made on the coastal sediments of the country since 1940s, it is only after the establishment of the National Institute of Oceanography (NIO; Goa) and Oil and Natural Gas Commission (later changed into a Corporation; Dehra Dun) that serious attempts were initiated to study the sediments off Indian coast. In the initial stages, the studies of NIO were confined to the sea bed sediments and fauna, based on ocean bottom samples and a few shallow core samples. This led to our understanding of the morphology of the continental shelf and slope, oscillations in sea level, trace elements geochemistry and microfauna in different traverses offshore. Dating of some samples was done, which led to establishing the chronology among some of the Quaternary sediments.

On the other hand, the primary interest of ONGC was exploration for hydrocarbons, which required understanding the stratigraphy and structure of the offshore basins all along the Indian continental margin from Bengal in the east to Kutch in the west, and also offshore Andaman-Nicobar islands (Fig.12.1). Besides, the detailed stratigraphy and structure of the Tertiary and Mesozoic in turn helped in the interbasinal correlation of data in different offshore basins, some of which are extensions of coastal onland basins only.

Whereas basic geological information is of importance in interpreting any subsurface data, it should be mentioned that advances made in concepts of sedimentation, techniques in geophysical surveys, and morphology and palaeoecology of microfauna, have greatly helped in unravelling the stratigraphy of the offshore basins. The structural style of the basins could only be explained based on plate tectonic concepts (except in intraplate regions), and more knowledge from similar basins elsewhere in the world. The vast amount of geophysical data acquired in offshore areas help in identifying the surface structural configuration and interpreting the tectono-sedimentary evolution of the basins by integrating floral and faunal data.

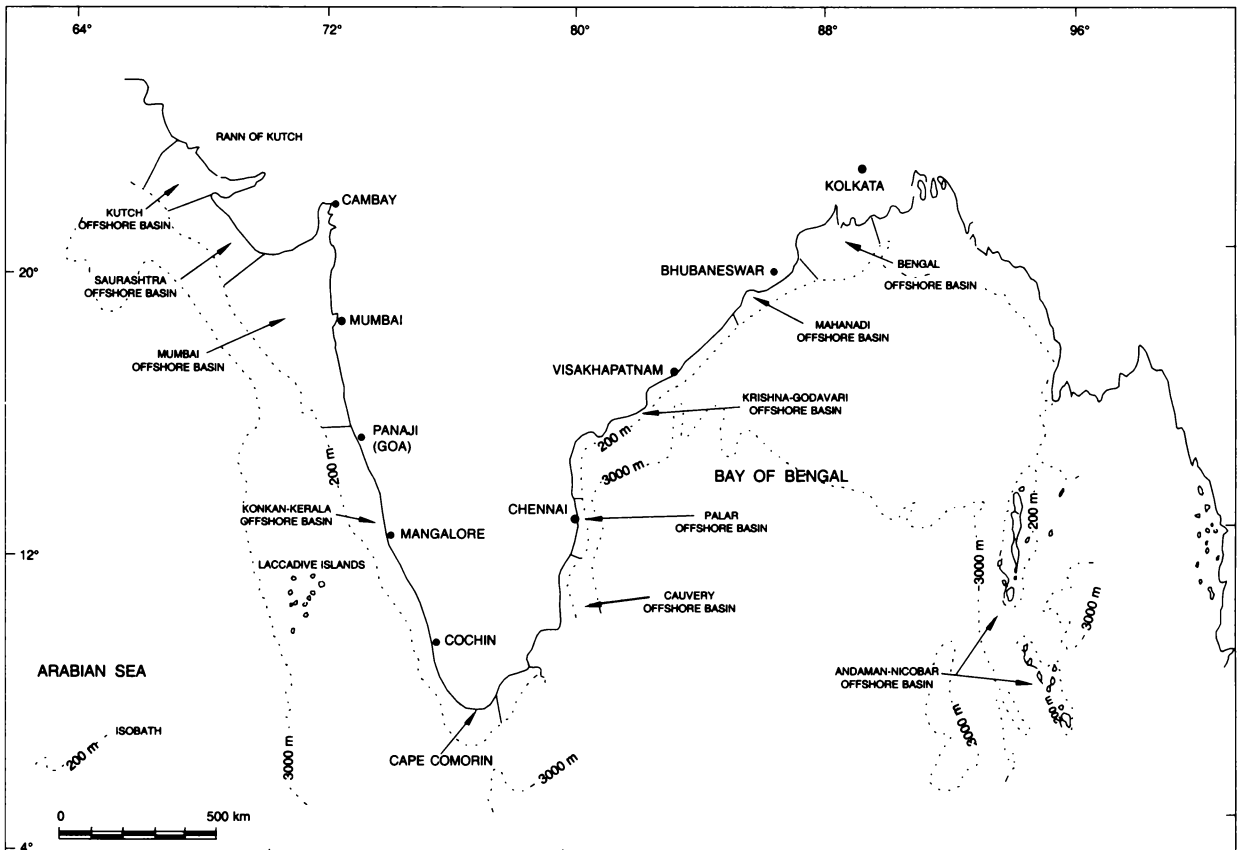


Fig.12.1. Offshore basins of India (modified after Srinivasan and Khar, 1995).

Detailed studies of planktonic foraminifera, ostracodes and palynofossils enabled detailed demarcation of zones and arriving at European and equivalent Indian Stages, particularly in Cretaceous, Paleogene and Neogene Systems. To start with, planktonic foraminifera were used and then ostracodes and nannoplanktons (at least for Paleocene to Mid-Miocene strata) and then the palynofossils (mainly dinoflagellate cysts). Figure 12.2 presents the different zonal markers with biostratigraphic control for Indian Stages based on planktic and larger foraminifera. This data helped in correlation and also aided in the recognition of hiatuses and sea level fluctuations. The significance of benthic foraminiferal study in the palaeoenvironmental interpretation is now realised by all explorationists.

Studies of palynofossils (spores and pollen, dinoflagellate cysts, acritarchs, calcareous nannoplanktons, diatoms and silicoflagellates) helped in hydrocarbon exploration, namely in (i) dating of sediments, (ii) biostratigraphy and thermal maturity of sediments, (iii) correlation of near coastal and deltaic sediments, and (iv) palaeoenvironment and palaeoclimatic reconstruction. Palaeoenvironmental interpretation based on integration of micropalaeontological, palynological and sedimentalogical data is the most powerful tool in this exploration effort. Plate 12.1 presents a few species of dinoflagellate cysts ranging in time to different periods from Cretaceous to Neogene.

It must be mentioned that with the fast changing concepts in the fields of structure and sedimentation, development of newer technology to study properties of sediments, better understanding of the palaeoecology of the numerous microfauna that inhabited the water bodies of the past, there has been a continuous change in the interpretation of the geology of the offshore basins. Interpretation of the subsurface stratigraphic data is a dynamic one; if any new well drilled in a basin revealed more information in terms of lithounit or geological age through fossils, it may change the earlier understanding of the subject. Being an interpretative and intuitive analysis, surprises are bound to come in a relook.

STRATIGRAPHY AND STRUCTURE

Following is a brief introduction to some aspects of the stratigraphy and structure of the major offshore basins of India.

Bengal Basin

It is partly located in the northeastern part of the Indian Peninsula and also offshore. The basinal area comprises of 57,000 km^2 on land, and 32,000 km^2 offshore up to 200 m bathymetry. Stratigraphy of Bengal Basin is

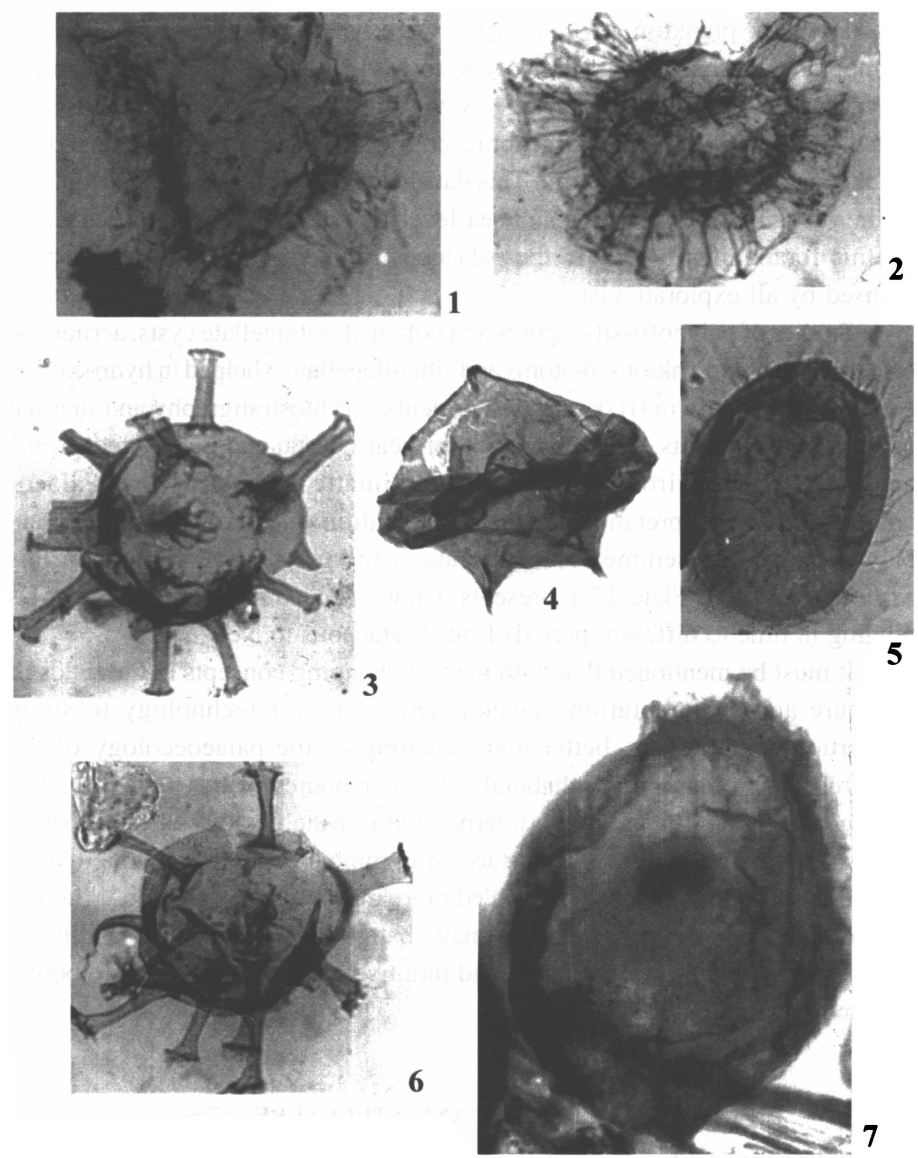


Plate 12.1. Cenozoic Flagellate cysts. **1.** *Glaphyrocysta ordinata* (Late Paleocene to Early Eocene), **2.** *Adnatosphaeridium multispinosum* (Early Eocene to Middle Eocene), **3.** *Homotrybilum plectilium* (Middle Eocene to Early Miocene), **4.** *Lejeunecysta hyalina* (Middle Eocene to Holocene), **5.** *Eocladopyxis paniculata* (Late Palaeocene to Middle Eocene), **6.** *Hystrichosphaeridium tubiferum* (Early Cretaceous to Early Eocene), **7.** *Damassadinium californicum* (Danian). (Courtesy: D.S.N. Raju).

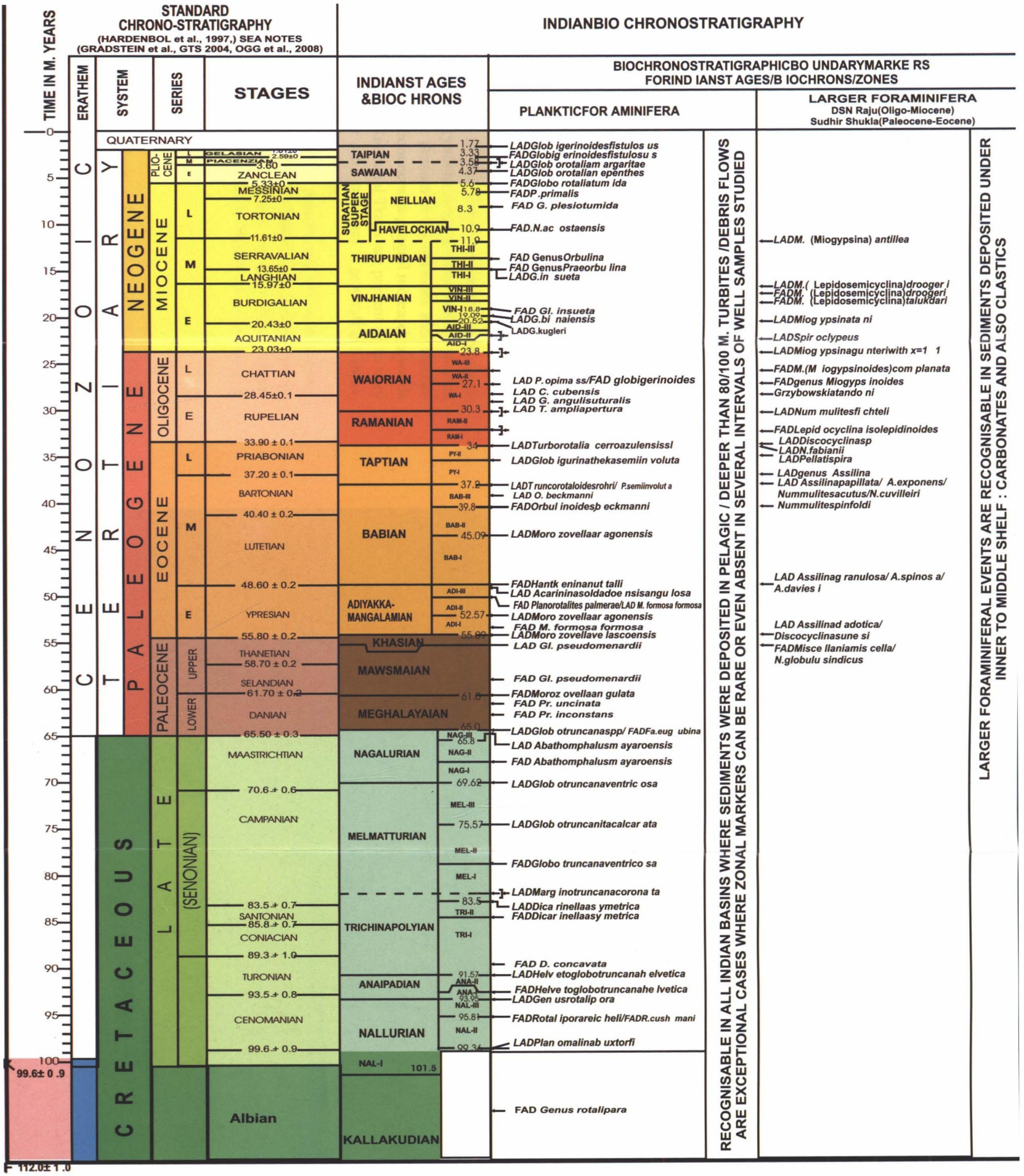


Fig.12.2. Cretaceous and Cenozoic biochronostratigraphy (stages and biochrons) : Standard and Indian. Compiled by D.S.N. Raju *(Personal Communication).*

known mainly from subsurface well data and seismic, gravity and magnetic surveys.

It is a polycyclic basin. It is flanked by the Indian Shield and Shillong massif to the west and north respectively and continues under an alluvial cover towards Bangladesh in the east and beyond. It owes its origin to complex tectonic activities operating over a long interval of time. It developed as an intracratonic rift basin, through Late Palaeozoic to Middle Mesozoic times (Gondwana Basin) and subsequently changed into a passive margin basin during Late Mesozoic time. The intensification of rifting resulted in the widespread volcanic effusion, which filled and subsequently levelled the entire relief of Gondwana palaeo-valleys.

Lower Gondwana Formations are met with in the subsurface as well as in the outcrops in the western part of the basin. Over the succeeding Rajmahal Traps occur Cretaceous Dhanjaypur Formation (transgressive shale) followed by Bolapur Formation – all made up of sandstone and siltstone. Ghatal, Jalangi and Sylhet Formations represent the Paleogene. The last one, Sylhet Formation is made up of limestones, glauconitic sandstones and shale. These and the others of the Neogene are given in Fig.12.3.

Mahanadi Basin

The Mahanadi Basin has an area of about 55,000 km^2 on land and about 14,000 km^2 shallow offshore. Sedimentary rocks ranging from shallow marine to continental (deltaic) environments are present in the offshore and onshore areas. The thickness of the sedimentary sequences in general increases towards southeast. Volcanic rocks equivalent to Rajmahal Traps are present up to very shallow water part of the basin. Table 12.1 presents a generalised litho-stratigraphic column of Mahanadi offshore basin.

In this basin, three distinct tectonic stages namely pre-rift (intercratonic stage), rift valley (pre-break up and break up stages) and post-break up marginal sag basin stage have been recognised. There are a number of ridges and depressions, identified based on interpretation of bouger gravity anomaly map and aeromagnetic total intensity maps.

Krishna-Godavari Basin

This basin contains sedimentary columns ranging in age from Late Carboniferous to Holocene. The older among them are exposed and most of the younger are in the subsurface. The NE-SW - trending Krishna-Godavari (K-G) basin is superposed on the NW-SE extending Pranhita-Godavari (Gondwana) Basin. Number of cycles of deposition have been recognised.

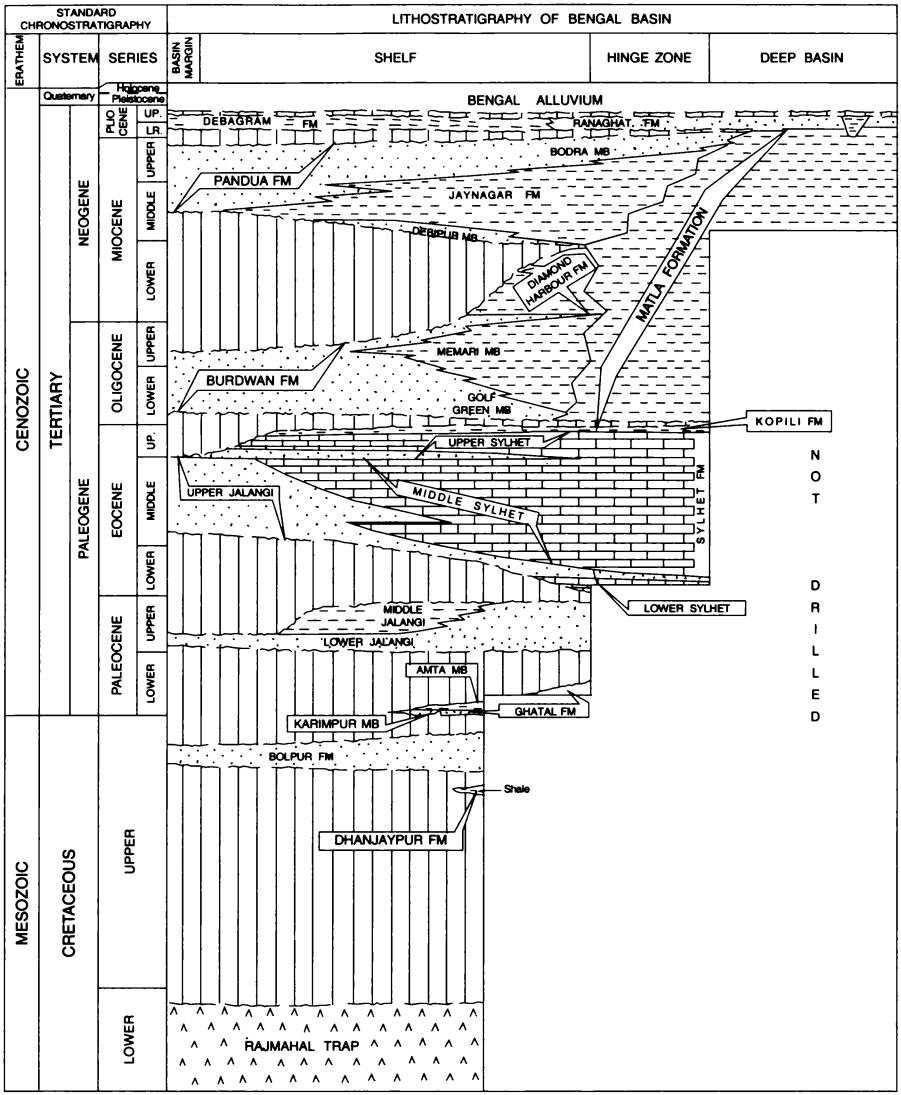


Fig.12.3. Lithostratigraphy of Bengal Basin (Source: Pandey and Dave, 1998) (Vertical lines indicate hiatuses).

The K-G Basin covers an area of 28,000 km^2 on land and about 24,000 km^2 up to 200 m isobath. Figure 12.4 represents a simplified litho-stratigraphic sequence in the basin. The basin is divided into sub-basins by fault-bound ridges. Most of the thickness of sediments is to be found in the grabens forming the sub-basins. The seismic section (Fig.12.5) presented here gives a general picture of the disposition of the sediments and the structural control.

A triple junction between Indian Peninsula, Australia and Antarctica is inferred at Masulipatam Bay, northeast of the present Krishna delta. The

Table 12.1. Generalised lithostratigraphic column of Mahanadi Offshore Basin (after Fuloria, 1993, p.359)

Age	Lithology	Depositional Environment	Thickness Range (m)
Recent - Pleistocene	Sands, clays and silts Contact gradational to unconformable ~~~~~~~	Deltaic to shallow shelf	200-600
~~		~~~~~~~~~~~~~	~~~~~~~
Pliocene	Sands and clays Contact gradational to unconformable	Prodelta to marine	200-700
Miocene	Claystones, siltstones and sandstones, fossiliferous patchy limestones in the lower part	Deltaic to open marine	400-1500
Oligocene?			
~~	Contact unconformable ~~~~~	~~~~~~~~~~~~	~~~~~~~
Early-Mid Eocene	Fossiliferous limestones, Carbonaceous shales, Siltstones and sandstones	Shallow marine (Inner shelf)	200-400
~~	Contact unconformable ~~~~~	~~~~~~~~~~~~	~~~~~~~
Paleocene	Argillaceous limestones, shales, siltstones, sandstones	Deltaic to shallow marine	50-600
~~	Contact unconformable ~~~~~	~~~~~~~~~~~~	~~~~~~~
Late Cretaceous	Mainly sandstones with minor shales and limestones	Shallow marine (Shelf)	0-500
~~	Contact unconformable ~~~~~	~~~~~~~~~~~~	~~~~~~~
Early Cretaceous	Basalts, tuffs and intertrappean shales/claystones	Sub-aerial and sub-aqueous	25-850
~~	Contact unconformable ~~~~~	~~~~~~~~~~~~	~~~~~~~
Precambrian	Granites and gneisses (Basement complex)		

NW-SE trending Pranhita-Godavari graben is considered to be the failed arm of the triple junction. Reactivation of the NE-SW trending faults during continental break-up resulted not only in large block movements affecting the deposited sediments, but also led to the outpouring of the lavas resulting in the emplacement of the Deccan Trap. During the Tertiary, a general progradation of the delta due southeast is observed.

The tectonic elements consist of horsts (ridges) and grabens (sub-basins) approximately extending NE-SW and ENE-WSW (Fig.12.6). The basin was initiated by rifting during Late Palaeozoic with the formation of NW-SE trending graben-horst blocks. The occurrence of Gondwana sediments like those of Draksharama, Kommugudem and Mandapeta Formations indicates the existence of some older grabens. It is during Early Cretaceous that marine incursion took place and clastic sediments accumulated. At the close of the Cretaceous,

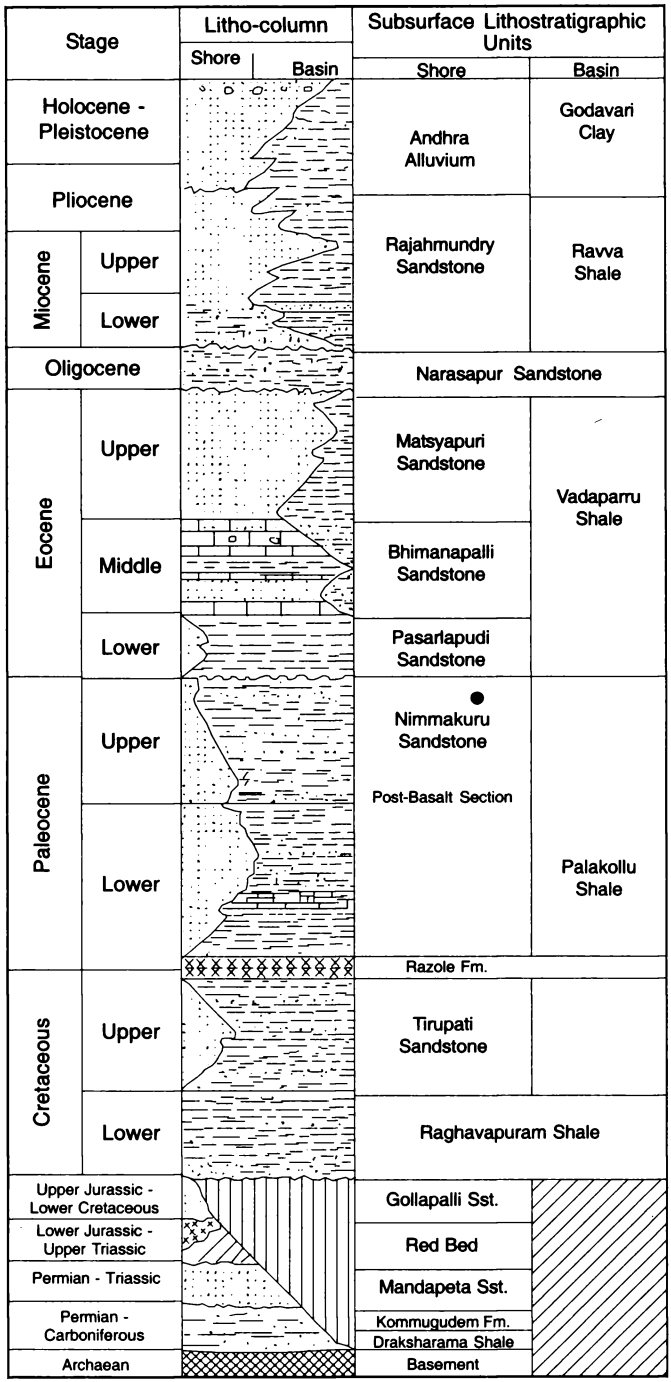


Fig.12.4. Lithostratigraphic nomenclature of sedimentary sequences penetrated in the basin. Wherever the continuity of the outcrop lithologic unit with the subsurface could be established, the same name is retained; otherwise, new rock stratigraphic nomenclature is suggested (after Rao, 2001, p.1632; AAPG © Dec. 11, 2003, reprinted by permission of AAPG, whose permission is required for further use).

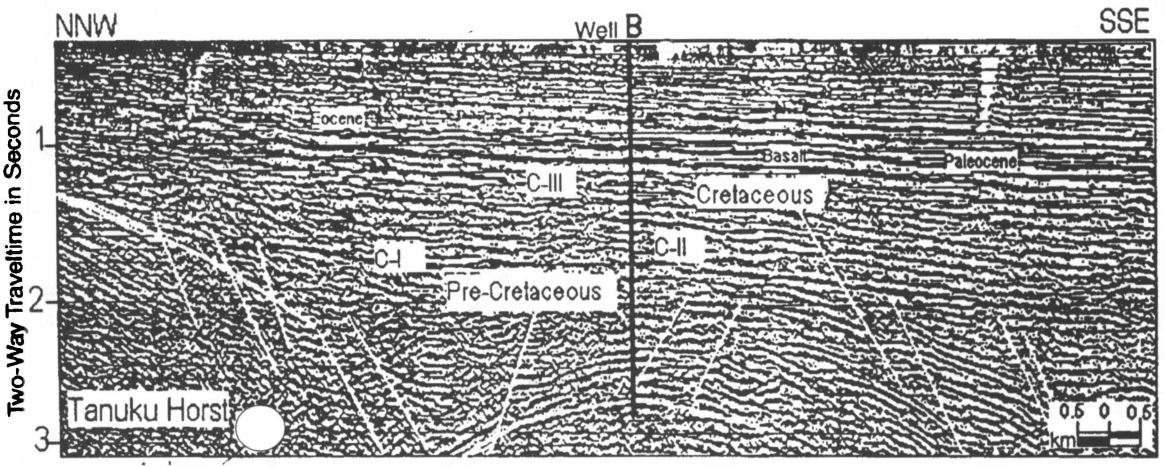


Fig.12.5. Seismic line across the East Godavari subbasin. Southeastern part of Tanuku horst (Mandapeta trough) showing older rift fill sequences superimposed with Cretaceous sequences (after Rao, 2001, p.1634; AAPG © Dec. 11, 2003, reprinted by permission of AAPG, whose permission is required for further use).

eruption of lava flows occurred. While during the Paleogene the sequences were essentially sandstones and shelf limestone, and during Neogene they were essentially deltaic clastics.

The known occurrence of oil on land in this region is from Early Cretaceous and Eocene horizons and in offshore from Neogene sediments. Gas occurrence on land extends from Permian to Eocene, though on offshore they are in Neogene.

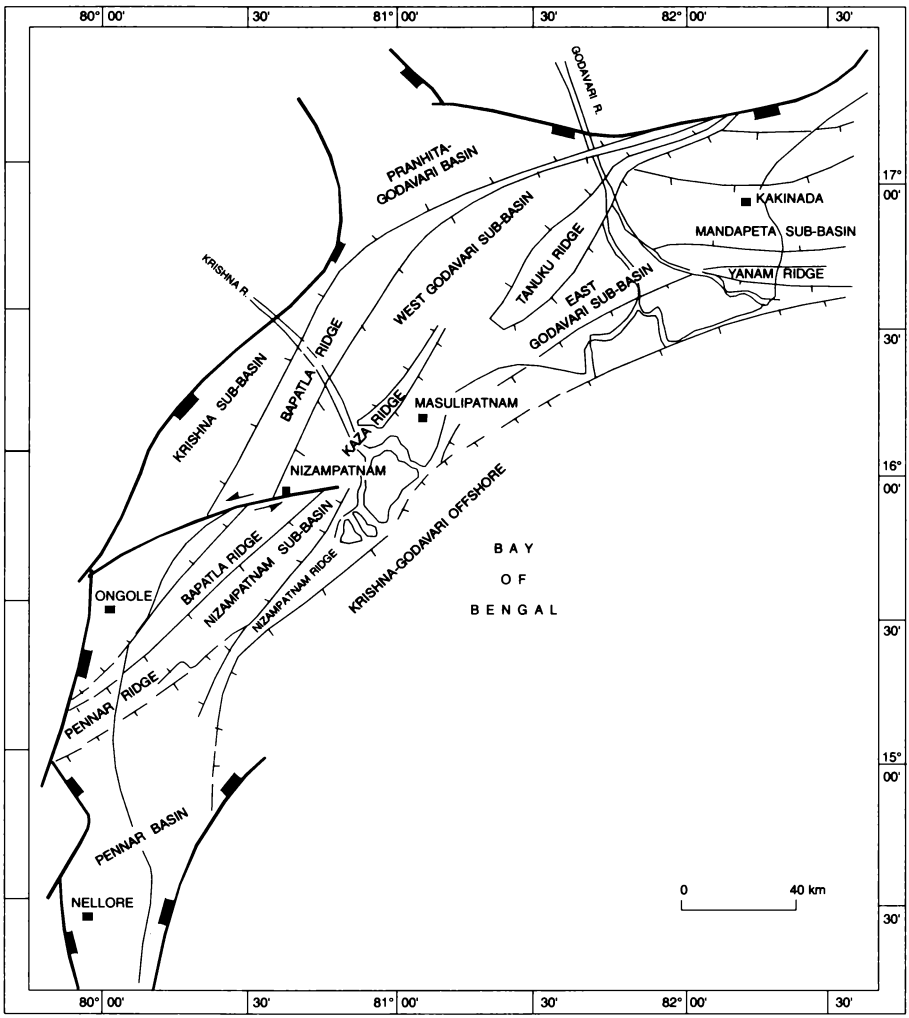


Fig.12.6. Tectonic framework of Krishna-Godavari Basin (modified after: Prabhakar and Zutshi, 1993, p.222).

Pennar Basin

This basin, though a minor one, does contain near shore to marine deposits, most of them met within subsurface only. The stratigraphy (Fig. 12.7) is based on offshore well data. The lithology is mostly made up of sandstones and

siltstones with a thin limestone band almost at the top, of Upper Cretaceous age. This is considered as a part of K-G basin.

Palar Basin

The sediment fill in the Palar basin is thinner compared to those in the other major coastal basins. A major section is essentially made of terrestrial deposits only with relatively minor marine deposits (Table 12.2 and Fig.12.7). Even this was initiated as a result of a rift and a major part of the sediment is a post-rift sequence.

The Late Jurassic and Early Cretaceous (Neocomian) formations are considered to be syn-rift sequence and those from Aptian onwards as post-rift sequence.

Table 12.2. Generalised stratigraphic chart for the Palar Basin (from Table 2 of Ranga Raju et al. 1993, p.376)

Age	Formation	Environment
Recent - Pleistocene	Alluvium Laterite Conjeevaram gravels	Continental
Mio-Pliocene	Cuddalore Fm. (Sst. with plant fossils)	Continental to ?Marine
Paleogene - Late Cretaceous	Undefined; claystones; thin sandstones	Marine
	~~Unconformity~~~~~~~~~~	
Early Cretaceous (Aptian)	Satyavedu Formation Sandstones; plant fossils	Continental
Early Cretaceous (Neocomian)	Transgressive overlap Sriperumbudur Formation (Shale, Sandstone; plant fossils; coal streaks)	Near coastal - Continental
Late Jurassic?	?	
	~~Unconformity~~~~~~~~~~	
Early Permian	Ongur Formation (equivalent to Talchir Fm.; Lower Gondwana; Boulder beds and splintery green shales)	Fluvio-glacial
	~~Unconformity~~~~~~~~~~	
Precambrian	Eastern Ghats - Crystalline rocks	

Cauvery Basin

The basin covers an area of about 25,000 km^2 on land and about 30,000 km^2 in the offshore, up to a depth of 200 m. The stratigraphic sequence is presented in Fig.12.8.

The basin formed during Late Jurassic to Early Cretaceous as a result of

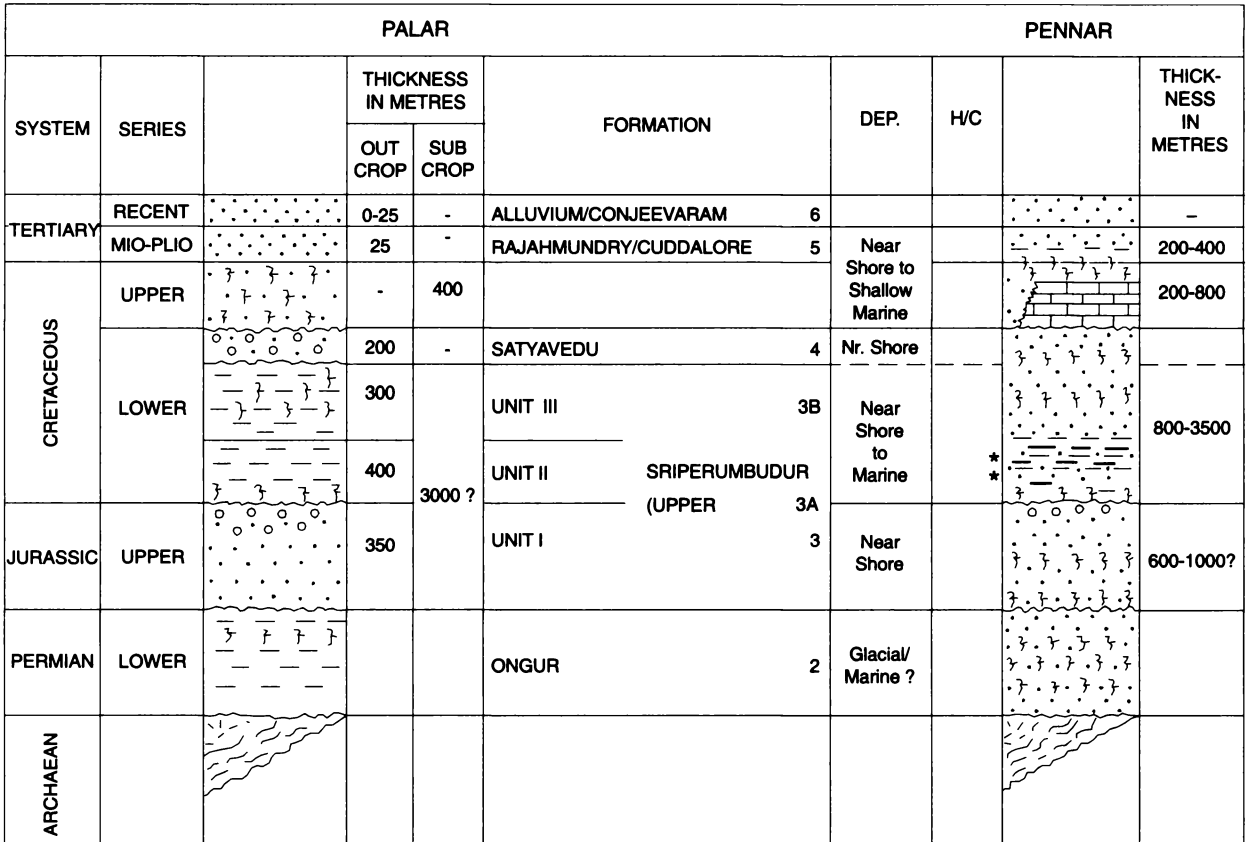


Fig.12.7. Stratigraphy of Palar and Pennar basins (Palar basin after Arunachalam and Pal, 1979; Pennar basin based on Well A & B in Offshore) (Source: Vairavan, 1993).

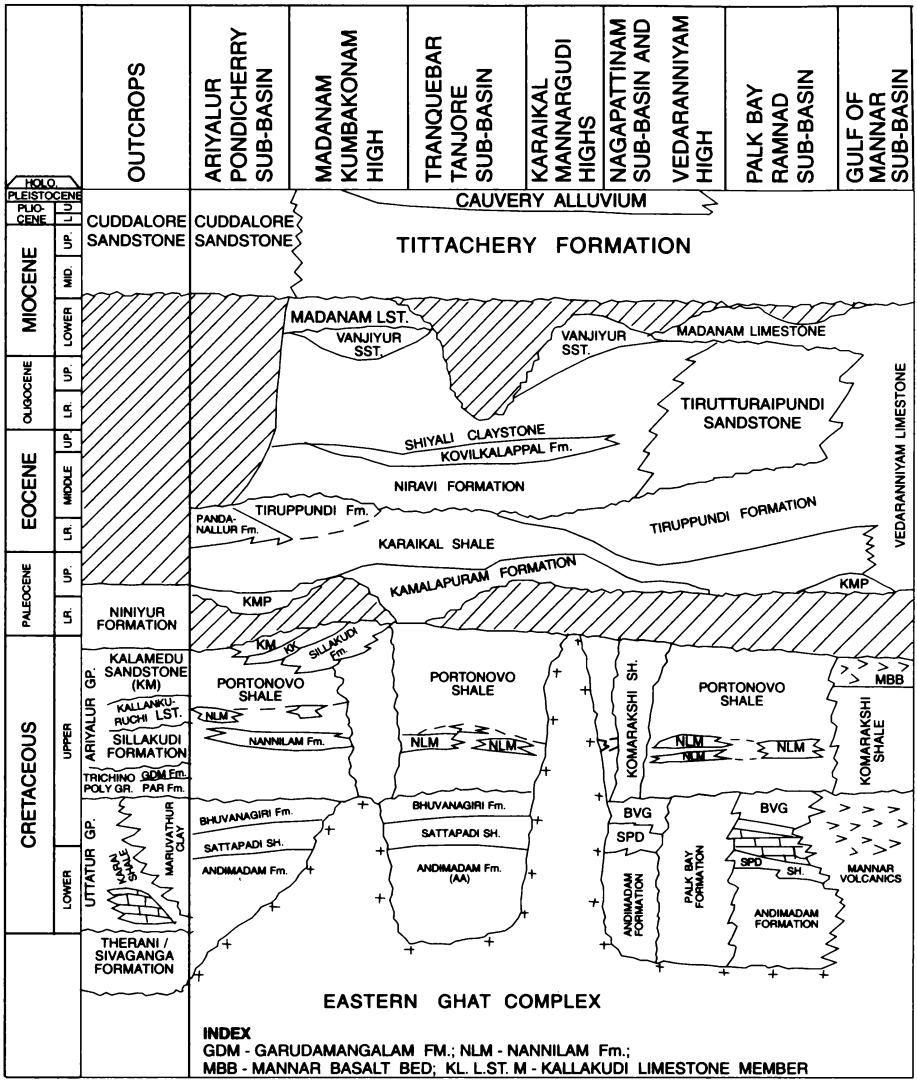


Fig.12.8. Stratigraphy of Cauvery Basin (adopted from Pandey and Dave, 1998).

fragmentation of the Precambrian basement into a series of horsts and grabens in response to crustal tensional tectonics. These resulted in the formation of ridges and sub-basins (Fig.12.9), most of them extending NE-SW. Sedimentation in the early stages were essentially arenaceous and non-marine. The first marine incursion took place in Albian in Cretaceous and that is how planktonic foraminifers and ammonite zones could be established from Albian onwards (Fig.12.10) to almost to Maastrichtian, when the rift phase got terminated. The post-rift sedimentary sequences appear to have prograded to the east. Several structural blocks and sub-basins were formed to start with,

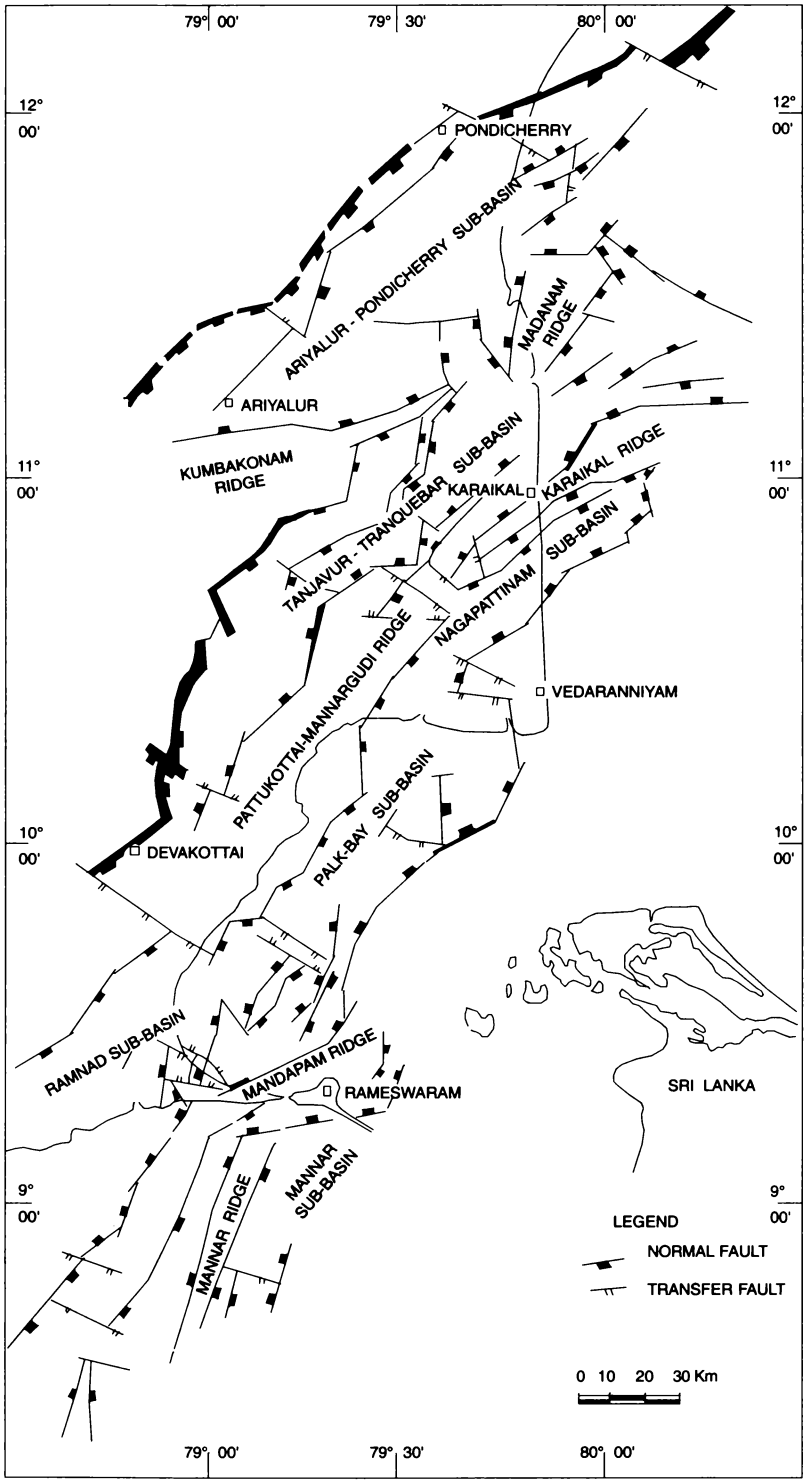


Fig.12.9. Tectonic map of Cauvery Basin (modified after: Prabhakar and Zutshi, 1993, p.225)

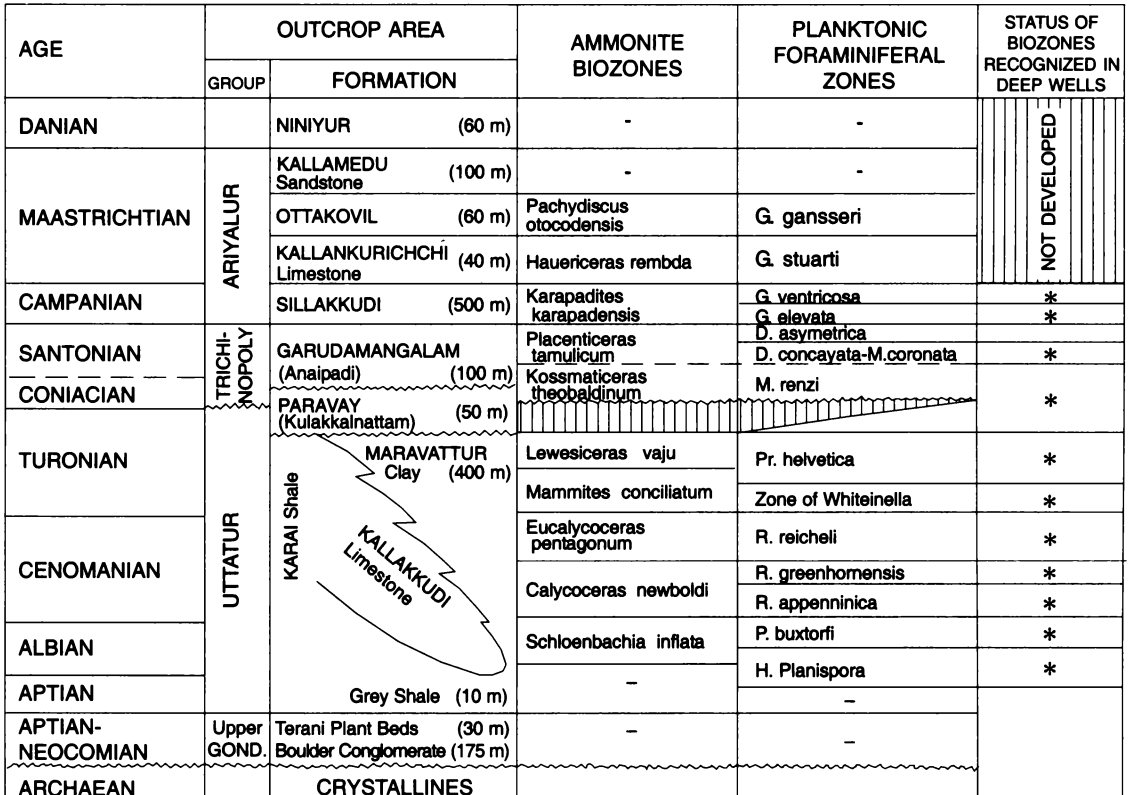


Fig.12.10. Stratigraphic succession, established biozones in the outcrop and subsurface Cauvery Basin (Tiruchirapalli area) Tamil Nadu, India (source: Govindan, 2000)

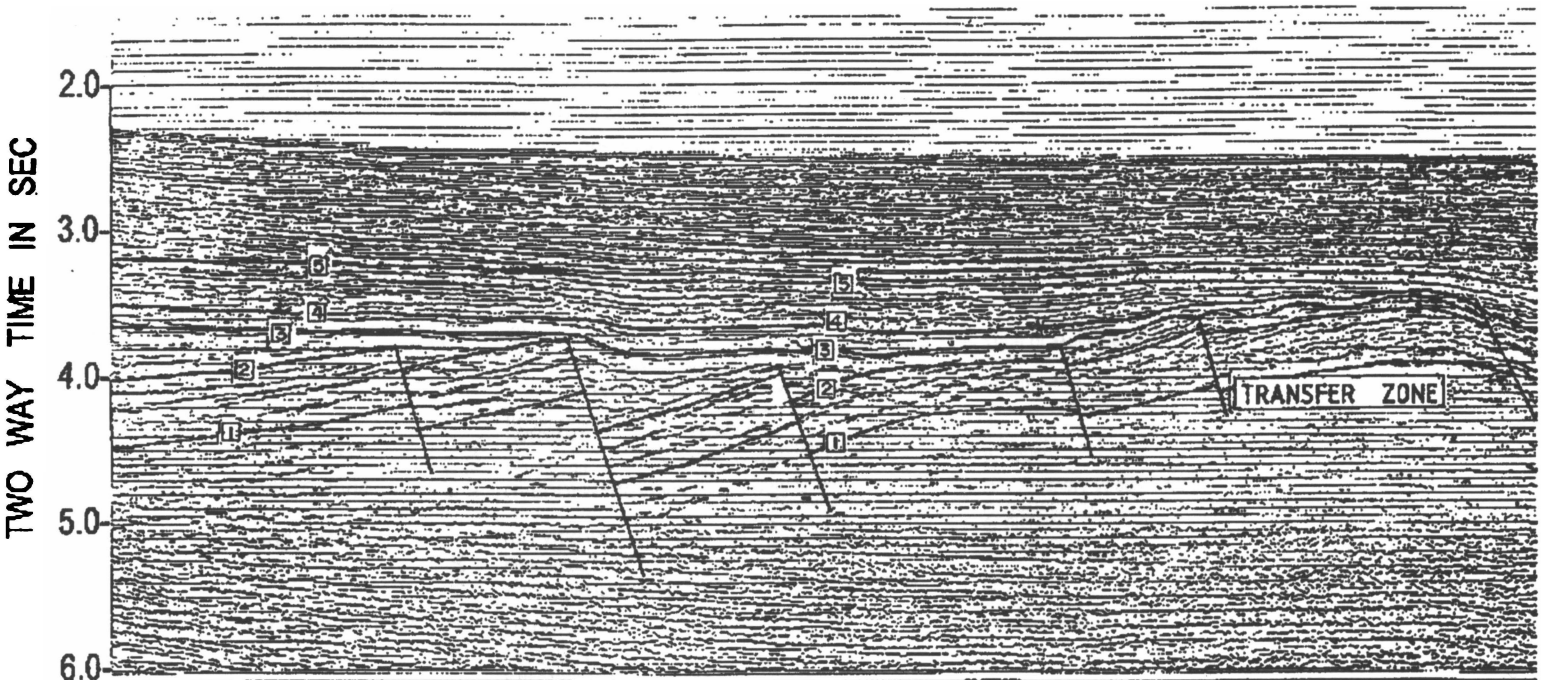


Fig.12.11. Representative transverse seismic across the northern part of the Konkan deepwater basin showing the rifts and tilt blocks. **1.** Basement, **2.** Base Tertiary, **3.** Top of Lower Eocene, **4.** Within Oligocene, **5.** Top of Middle Miocene. 1-2 is pre-rift, 2-3 is syn-rift, 3-5 is post-rift (older) (after Thakur et al. 1999).

followed by vertical–lateral movements resulting in tectonic reversals of pre-existing horst-blocks and consequent development of submarine valleys and hiatuses in deposition. A number of hiatuses were recognised not only with the help of seismic sections, but more based on microfaunal studies. The known occurrences of hydrocarbon are mainly from Cretaceous and Paleocene-Oligocene sequences. The well in Narimanam field of Tamil Nadu penetrates Oligocene clastic reservoirs.

Konkan-Kerala Shelf

The sedimentary section in Konkan deepwaters, off the west coast of India, is beyond the Kerala-Konkan continental shelf. Beyond a water depth of 2000 m, the Konkan ocean floor topography is gentle and merges with the Arabian abyssal plains. The regional structural elements of the western contiental margin of India run parallel to the coast right from Kutch in the north to Cape Comorin in the south (Fig.1.11).

The rifting is inferred to have taken place after the break up of Madagascar around 85-90 Ma initiating a system of north-south rift segments. Structure and stratigraphy has been worked out mainly based on regional seismic data and wells drilled over the Konkan-Kerala shelf. One of the seismic sections presented here (Fig.12.11) helps in clearly demarcating pre-rift, syn-rift and post-rift tectono-sedimentary stages. The geological transects drawn from west to east across the western continental margin in the Konkan basin show not only the broad extent of the various lithological units, but also many horsts and grabens, affecting the basement, volcanics and limestone horizons.

Unlike in the offshore basins of the East Coast, where fluviatile sediments are followed by the marine and among them arenaceous and argillaceous sediments usually predominating over calcareous ones, in this basin an almost continuous sequence of Tertiary sediments is met with over the Deccan Trap with a major part made up mainly of limestones (Fig.12.12). Another difference one notices is that on the East Coast there is a certain degree of continuation of some of the stratigraphic horizons present in the land extending in the offshore and the later thickening of the younger sediments aided by many growth faults. In the Kerala-Konkan coast, there is absence of Mesozoic sediments on land and only patches of Neogene sediments are present.

Bombay Offshore Basin

This is perhaps one of the largest offshore basins investigated in very great detail mainly because of continued exploration and production of oil from many of the wells here. The basinal area is about 1,16,000 km^2 up to

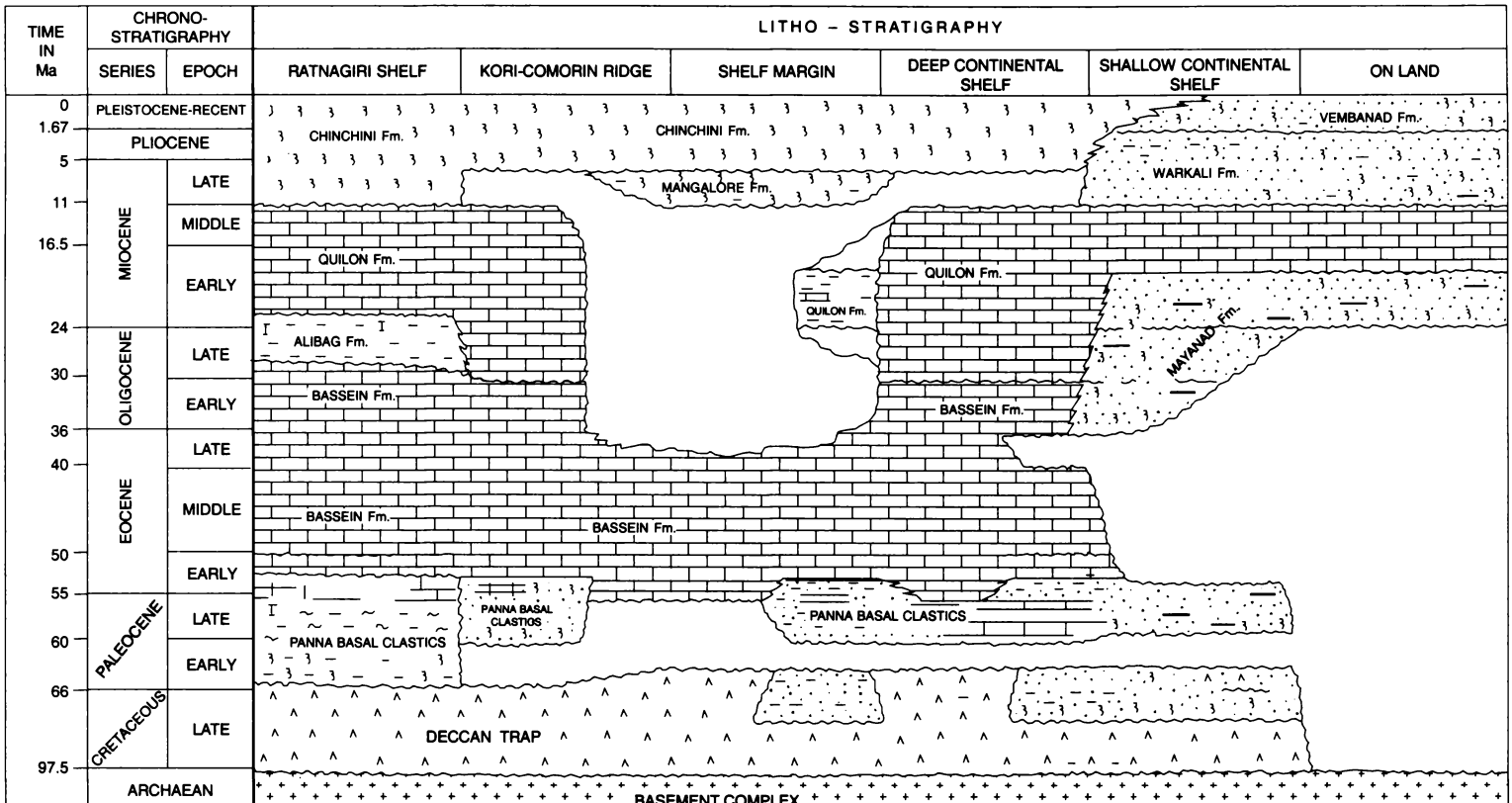


Fig.12.12. Lithostratigraphic units of Kerala-Konkan Shelf (modified after: Pandey and Dave, 1998, p.35).

200 m isobath (Fig.12.13). Towards northeast the basin gets linked through the Gulf of Cambay to the onland Cambay basin.

By and large Deccan Trap forms the basement except in a few places where the sediments lie over Archaean. There is almost a continuous sedimentation with minor breaks only right from the rift stage to post-rift stage,

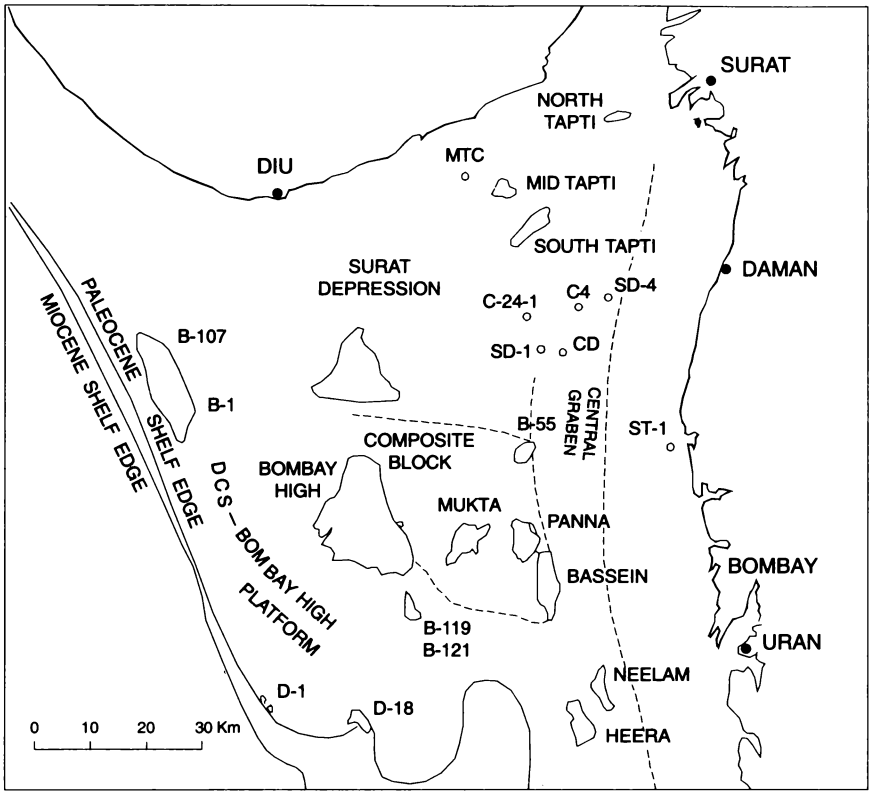


Fig.12.13. Bombay Offshore Basin (Courtesy: A. Govindan).

extending from Paleocene to Pleistocene. Figure 12.14 presents stratigraphy of the offshore basin. One of the characteristics of the basin is the occurrence of numerous horizons of limestones and calcareous shales, amidst the arenaceous and argillaceous elements in the basin. This has necessitated intensive study of the nature of the limestones from various angles – texture, chemical composition, facies modelling and faunal content in order to differentiate the carbonates. The hydrocarbon production is mainly from the carbonate reservoirs. The utility of the palynofossils can be seen from the presence and recognition of the First Appearance Datum (FAD) and Last Appearance Datum (LAD) of dinoflagellate cysts and establishment of zones assisting correlation (Fig.12.15). In the figure the stratigraphy is also represented along with lithological units of sandstone, shale, limestone and others above the Deccan Trap.

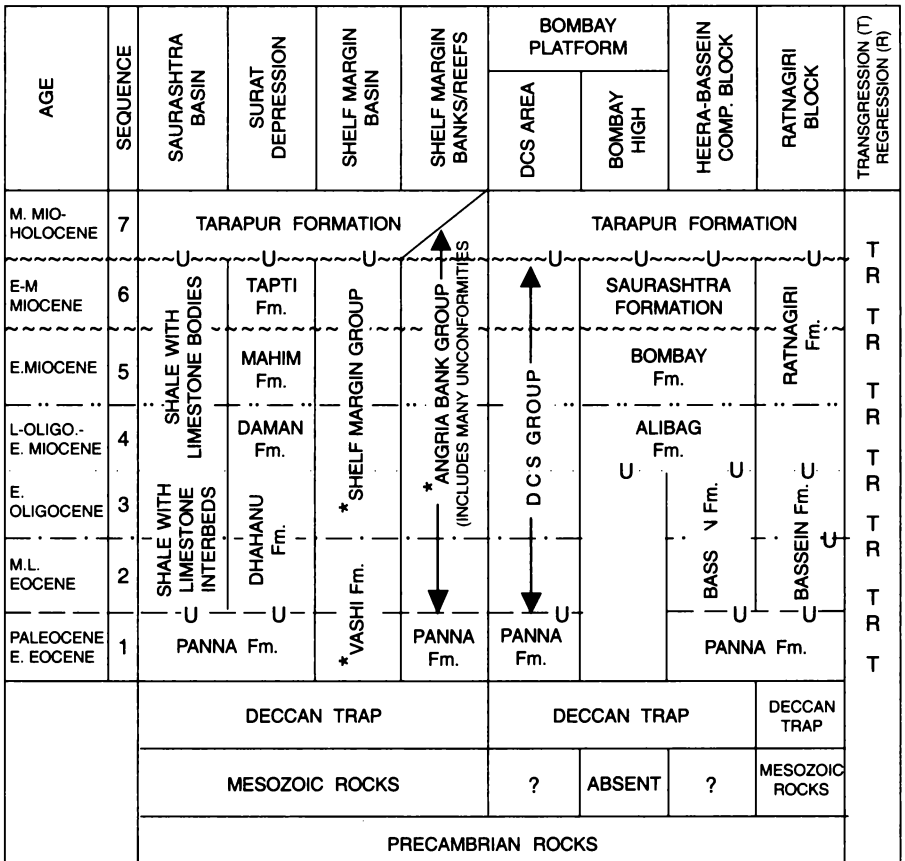


Fig.12.14. Stratigraphy of Bombay Offshore Basin (after Nair et al. 1992, p.420). * - Newly proposed informal names.

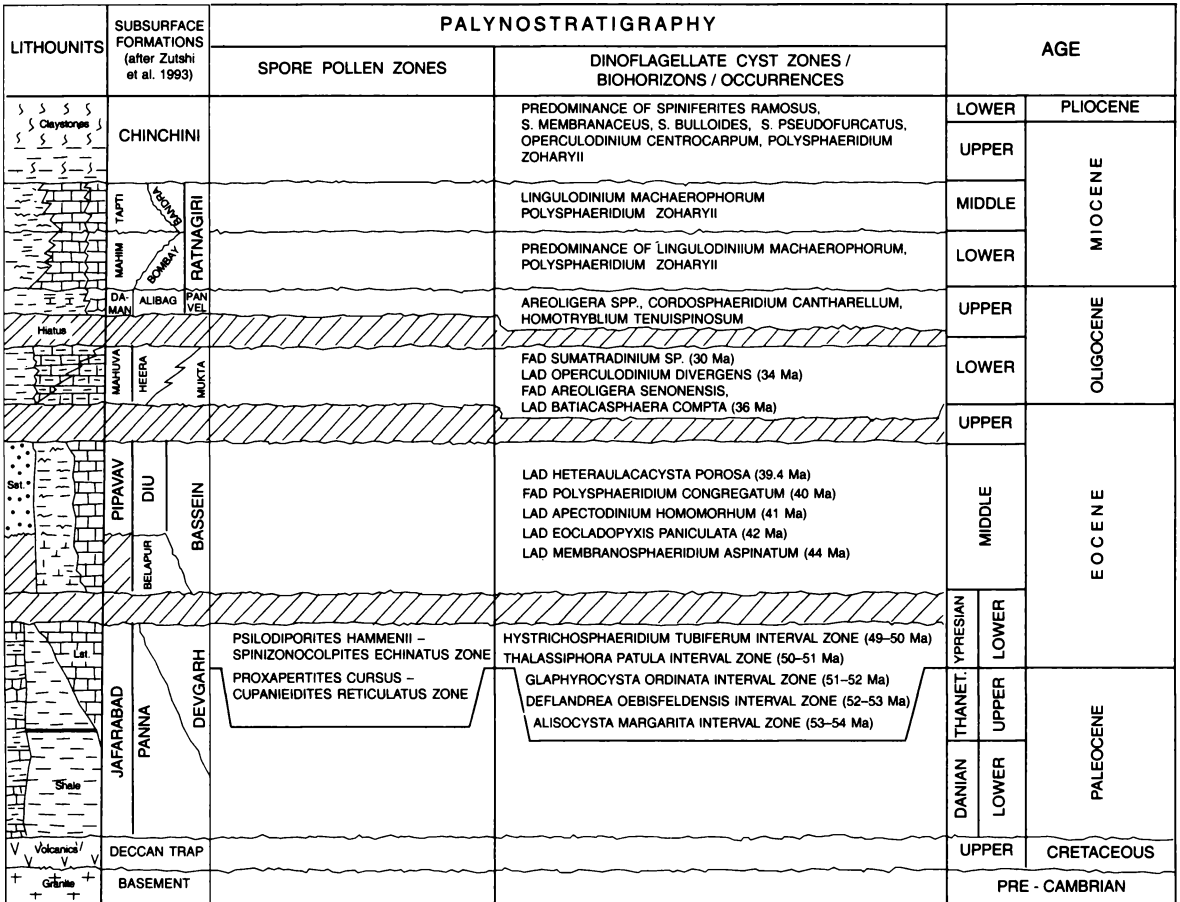


Fig.12.15. Generalised palynostratigraphy and lithostratigraphy of Bombay Offshore Basin (source: Mehrotra et al. 2002).

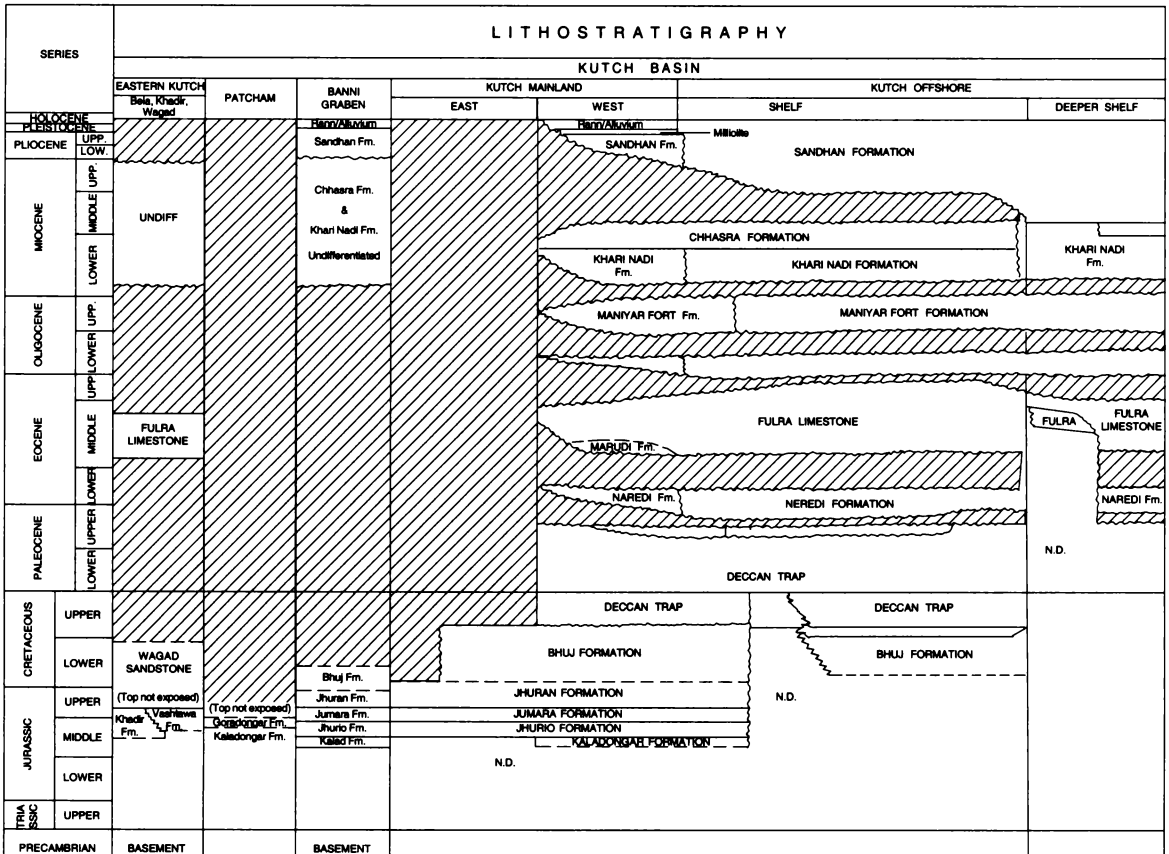


Fig.12.16. Rock stratigraphic succession of Kutch Basin (source: Pandey and Dave, 1998, p.29). Hiatus

The western margin evolved through early rift and post-rift phases of divergent margin development. A series of regional and local horsts and grabens resulted in response to rifting along the dominant basement trends. The structural style of Mumbai offshore basin is one of normal fault setting in a rift system with major associated antithetic faults. In the region of Mumbai (Bombay) offshore, a basin-wide unconformity, recognisable in seismic sections, is dated close to Middle-Late Paleocene. This marks the end of the early rift phase. Towards the end of this phase, most of the rift-related grabens and horsts, located in the interior graben systems, were filled with sediments. The post-rift sedimentary sequences represent deposition contemporaneous with passive subsidence of the continental margin during the drift of the Indian Plate. The overall shelf depositional system is comprised of deltas, clastic and carbonate tidal flats, strand plains and carbonate 'ramps,' platform limestones and banks. The hydrocarbon production is mainly from Eocene and Miocene limestones.

Kutch and Saurashtra Basins

The northern limit of Kutch-Saurashtra basin continues to the north beyond the Indo-Pakistan border. The rock formations are continuous to the north of this boundary. The southern part is also continuous with the Bombay offshore basin. In the mainland Saurashtra, only the coastal has a few outcrops of Neogene. Offshore sediments of parts of Cenozoic have been met with over the Deccan Trap.

The stratigraphy of the Mesozoic and Tertiary formations has been worked out in considerable detail on the Kutch mainland. Though there are many gaps in the sequences in Eastern Kutch, Patcham and Banni graben, Kutch offshore contains relatively a fairly continuous sequence (Fig.12.16) from the Deccan Trap onwards. The Kutch basin covers an area of about 38,000 km^2 on land and 13,000 km^2 offshore up to 200 m isobath. Structurally right from off Saurashtra coast, a series of approximately sub-parallel E-W arches (ridges) have been identified from south to north. These are named Mainland ridge, Wagad ridge, Island ridge and Nagar-Parkar-Tharad ridge. These ridges are offshore continuation of the uplifts mapped on land. In a way, these are responsible for the structural and geomorphic control of sedimentation, particularly in Kutch offshore.

Andaman-Nicobar Basin

This basin occupies an area of 6000 km^2 on land and about 41,000 km^2 offshore up to 200 m isobath. This basin forms a part of a major island arc system of convergent margin extending from Myanmar in the north to Indonesia in the south. It probably came into existence as an arc trench system and as a

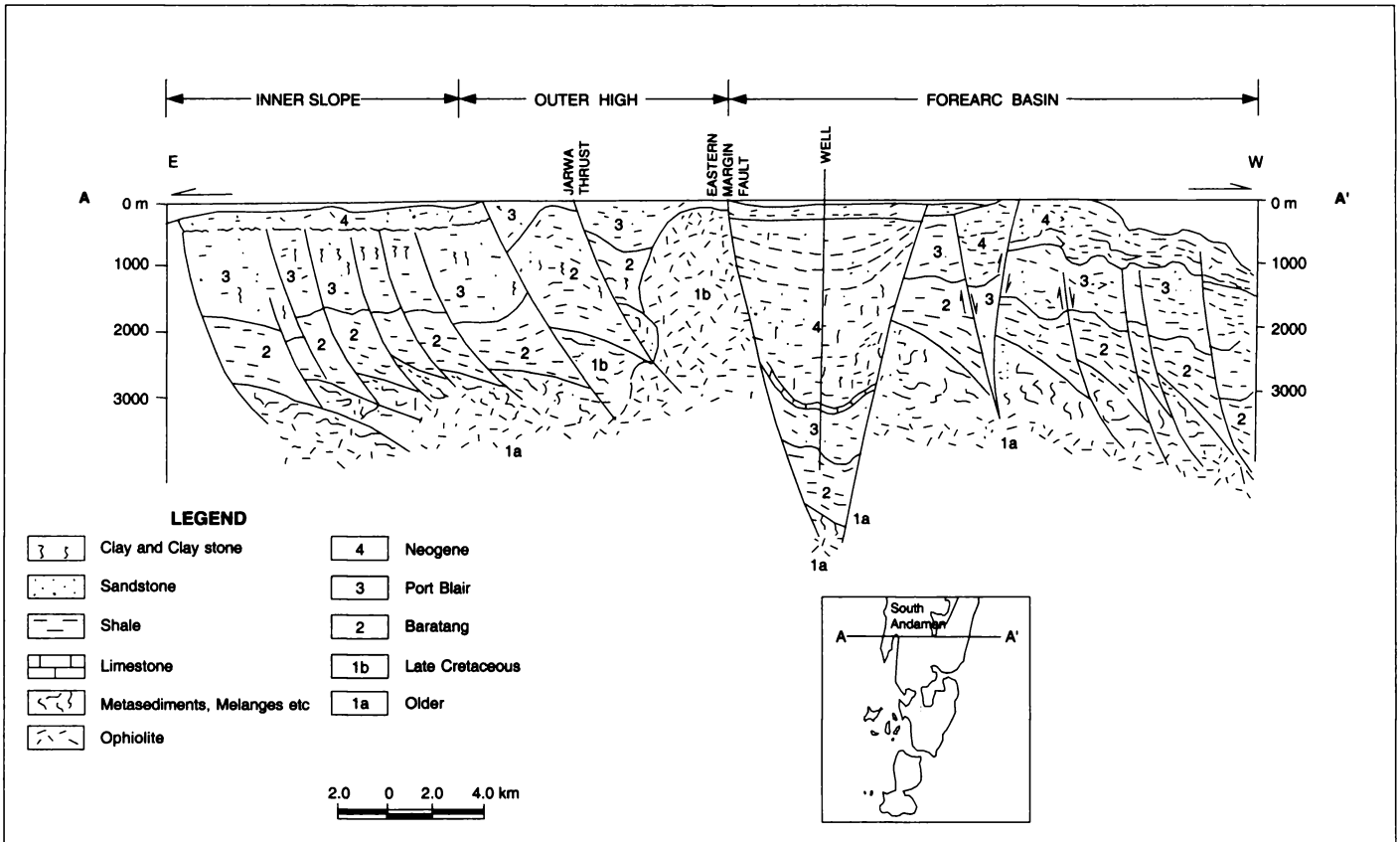


Fig.12.17. Geological section across south Andaman (source: Roy, 1983, p.41).

result of northward movement and anti-clockwise rotation and subduction of the oceanic plate (eastern part of Bay of Bengal) beneath the Asiatic Plate since Cretaceous times.

In the island part of the basin, the succession comprises about 3400 m of Port Meadow Formation (Cretaceous), Baratang Formation (Late Cretaceous to Late Eocene), Port Blair Formation (Oligocene) and volcanics. The Neogene strata of about 2000 m thick, divided into Strait, Round, Guitar and Long formations, include calcareous, argillaceous and arenaceous facies in the same order of dominance. Table 12.3 gives the sequence of formations in the Andaman Basin.

As one proceeds from west to east, say along 10°N Latitude, the tectonic elements met with are: Outer slope, Andaman trench, Inner slope, Outer high, Fore arc basin, Trench slope break, Volcanic arc and Back arc basin. The main Andaman Island forms the outer high/trench slope break. The islands are represented by N-S trending tight folds, associated with several faults of same orientation (Fig.12.17). Some of the faults have throws ranging from 300-2400 m. The West Andaman Fault defines the boundary of the volcanic arc. The active volcanoes of Barren and Narcondam islands represent a part of volcanic arc. Back arc is a region of high heat flow. Recent oceanic crust and active spreading centre have been recognised in this belt.

Table 12.3. Lithostratigraphy of Andaman Basin (after Zutshi and Panwar, 1997)

<table>
<tr><td>Chrono-stratigraphy</td><td colspan="4">Lithostratigraphy</td></tr>
<tr><td></td><td>Main islands</td><td>Islands in Fore Arc basin</td><td>Subsurface</td><td></td></tr>
<tr><td>Pleistocene</td><td rowspan="4">Not Exposed</td><td>Neill Fm.
~~~~~~~~~~</td><td>Neill Fm.
~~~~~~~~~~</td><td rowspan="4">Archipelago Group</td></tr>
<tr><td>Pliocene</td><td rowspan="3">Long Formation
Inglis Fm.
Strait Fm.</td><td rowspan="3">Long Formation

Strait Fm.</td></tr>
<tr><td>Miocene U M L</td></tr>
<tr><td>~~~~~~~~~~~~~</td><td rowspan="6">Not exposed</td><td rowspan="6">Kalapani Formation</td><td>~~~~~~~~~</td></tr>
<tr><td>Oligocene</td><td>Port Blair Formation
~~~~~~~~~~~~</td><td rowspan="5">Andaman Group</td></tr>
<tr><td>Eocene</td><td>Baratang Formation (undifferentiated in North, South Andaman)</td></tr>
<tr><td>Palaeocene</td><td>~~~~~~~~~~~~</td></tr>
<tr><td>Upper Cretaceous</td><td>Port Meadow Formation</td><td>----------
Not encountered</td></tr>
</table>

The following Table 12.4, very general in nature, is presented to give an idea of the age and sediments from which hydrocarbons are being produced in the major basins of India.

Table 12.4. Age, Source rock, Reservoir rocks and Traps in Petroliferous basins in India (Biswas, S.K., *personal communication*, 2010)

Basin	Source Rocks	Reservoirs Rocks	Trap
Western Offshore	Paleocene-Early Eocene sediments (Panna Fm.) in Bombay offshore and Oligocene (Mahuva/Daman Fms.) in Surat Depression	Mainly Miocene, Mid Eocene-Oilgocene carbonates, also sandstones, and fractured Precambrian basement	Structural and strati-structural combination
Cambay	Paleocene Olpad Fm., Lr. Eocene Cambay Shale and Mid Eocene Kalol Fm.	Paleocene Olpad Fm., Mid-Eocene Kalol and Ankleshwar sandstones, sand lenses in Lr. Eocene Cambay and Up. Eocene Tarapur Shale	Structural and Stratigraphic combination
Upper Assam	Upper Paleocene-Eocene shales and coal-shale sequence of Oligocene Barail Fm.	Barail sandstones (Oligocene Tipam sandstones (Miocene) and fractured basement	Structural and Stratigraphic combination
Krishna-Godavari	1. West Godavari sub-basin Lr. Cretaceous Raghavapuram Shales 2. East Godavari sub-basin Up. Eocene Palakollu Shales 3. Offshore Ravva sub-basin Lr. Miocene Vadaparru Shales 4. Mandapetta (offshore) Permo-Carboniferous Kommugudam Fm.	Besides Paleocene-Eocene sandstone of Pasarlapudi Fm., Miocene sandstone of Ravva Fm., arenaceous sequences of different formations ranging from Paleocene to Pliocene	Structural-cum-Stratigraphic
Cauvery	Early Cretaceous shales of Andimadam and shales of Late Cretaceous Porto-Novo, Kudavasal and Sattapadi Fms.	Sandstones of Bhuvanagiri, Nannilam Fms. (Up. Cretaceous); Kamalapuram Fm. (Paleocene-Eocene) and Niraval Sandstone (Oligo.)	
Mahanadi, K-G and Cauvery Deep-water basins	Mio-Pliocene Shales	Pliocene sub-marine channel sands	Stratigraphic, strati-structural
Tripura-Cachar basin	Early Miocene, Lr. Bhuvan Shales in Tripura and Up. Oligocene Renji-Jenam Fms. of Cachar	Oligocene Renji and Miocene Bhuban and Bokabil Sandstones	Mainly structural, also combinations
Rajasthan Basins	Shales of Lr. Cretaceous Pariwar Fm. and Up. Cretaceous Gour and Par Fms. in Jailsalmer basin and Paleocene Fatehgarh Fm. in Barmer basin	Cretaceous Goru and Par Fms. sandstones and Jurassic Jaisalmer limestone in Jaisalmer basin, Goru sandstone in Kharotar-Ghotaru area and Jurassic argillaceous limestone in Shahgarh basin. Fatehgarh sandstone in Barmer basin	Structural

Fm. - Formation; Lr. - Lower; Up. - Upper

13

Morphology and Evolution

INTRODUCTION

The term 'epeirogeny', which refers to one of the major processes that brings about the projection and existence of continental landforms, was introduced by Gilbert to describe broad gentle warping of large land surface. However, the minor warpings within an epeirogenically disturbed/modified landmass have been termed as 'cymatogeny' by L.C. King. Interpretation of landscapes involves delineation of the effects of faulting (local), epeirogeny (regional) and major sea level changes (eustatic) besides effect of exogenic causes like weathering and erosion.

A major part of the shield areas in the world are made up of planation surfaces, usually at high elevations, though later subjected to dissection and alteration due to various tectonic changes and exogenic processes. A planation surface is defined as a non-relief forming, denudational topographic surface. Many large planation surfaces are polygenetic, i.e. parts of them can be erosional, depositional, etch plains etc. All land surfaces, from the moment they are exposed to the atmosphere, are susceptible to denudation. They are thus dormant to more or less active surfaces, depending on their distance from fluctuating base levels and receding stream heads at any moment in time.

The Gondwana landscape, which is the oldest landscape in some of the southern continents, is defined as the one that existed before the Gondwana broke into several parts, became individual entities and acquired the present shapes, though not necessarily the present positions. Lester King correlated world's plainlands and inferred that there are three to four major correlatable surfaces in some parts of the southern continents in Gondwana. This correlation has limitations as most of these surfaces have been repeatedly affected and altered by later exogenic and endogenic forces.

The Indian subcontinent has been divided into Peninsular India, Extra-Peninsular India and Indo-Gangetic Plain. The collision of Peninsular India and the Mainland Asia resulted in the break-up of the Indian crust and subsequent

uplift of the Himalaya along numerous thrust sheets and formed the Extra-Peninsular India. The intermittent uplift in varying pulses of the Himalaya caused denudation by numerous rivers that led to the deposition of vast thickness of sediments forming the Indo-Gangetic Plain to its south. The different parts of the Indian subcontinent have undergone varying effects of endogenic and exogenic processes complicating the sequence of geomorphic history of the subcontinent. Study of the geomorphology of the parts, taken together, do not necessarily lead to the understanding of the geomorphology of the whole, unlike in the case of geological history, wherein the evolution of the subcontinent can be explained in terms of shield, craton, accretion, mobile belt, subduction, etc. In the following pages an attempt is made to highlight the morphology and evolution of the major and a few characteristic landforms of the Indian subcontinent.

The geological evolution of the different terranes in the Indian subcontinent has been traced since the Precambrian. Thrust tectonics, subsequent to continental collision, caused the juxtaposition of the various terranes in the Mesoproterozoic mobile belts in India. The major Early Proterozoic lineaments controlled the deposition of Gondwana sediments during Upper Carboniferous to Lower Cretaceous. The three major Gondwana basins namely Damodar, Mahanadi and Pranhita-Godavari are considered to be the result of Gondwana faulting and rifting (Fig.7.1). However, the geomorphic forms in Peninsular India have been shaped by the later endogenic and exogenic processes. The east and the west coasts of India formed around 130 Ma and 65 Ma ago respectively.

The geomorphic histories of the three regions of the Indian subcontinent have been partly controlled by their earlier geological history. The responses of global climate change, sea level and tectonism are engraved in each one of these regions. There have also been some responses in one region to something that happened in another. For instance, it is inferred that major faulting in Son-Narmada-Tapti (SONATA region) can be related to the uplifts in the Himalaya and similarly the uplifts in the Himalaya have had an effect on the nature and quantum of accumulation of sediments in the Ganga Plain and Bengal Basin. In spite of these, the three regions have had some degree of independent evolutionary history related to regional causes. Now this will be briefly presented with a few examples in the following three physical divisions of (i) Peninsular India, (ii) Extra-Peninsular India and (iii) Indo-Gangetic Plain. Conspicuous variations in morphology and sediment content can be found along the rivers in India in the above three physical divisions and the Thar region, due to monsoon floods, both in alluvial and bedrock channels.

PENINSULAR INDIA

Palaeosurfaces

Palaeosurfaces/planation surfaces have been studied in many parts of

India, since over five decades by many geographers and geologists; of particular interest are those occurring in parts of south India, Kutch, Rajasthan, Madhya Pradesh, Jharkhand (part of erstwhile Bihar), North-Eastern Region and Orissa. A brief account of the important palaeosurfaces recognised in these regions is presented here.

South India: The earliest account on the erosional surfaces in South India is of Mysore Plateau (southern part of Karnataka), followed by those, particularly in Tamil Nadu, Andhra Pradesh and Kerala. The recognition of these surfaces was mainly based on accordance of summits, discordance to structure, topographic breaks, occurrence of duricrusts etc. In south India at least 3 palaeosurfaces have been established. The age of the highest surface in south India over the Nilgiri Hills is debatable as to whether it is the oldest (Jurassic?) or much younger (early Cenozoic?), and positioned there due to block faulting or uplift. Some are of the view that its position is due to upwarps (caused by epeiorogeny) and erosion, as there is no direct field evidence of displacement of strata particularly on the southern side of the Nilgiri Hills and the adjoining Palghat Gap, a major valley across the southern *Sahyadri*. Some view the charnockite massif standing out prominently, as a resultant of hardness of rocks with limited porosity able to withstand weathering for a longer period compared to the adjoining greenstones and granites and thus stand up to great heights. To some, the very fact that high-grade granulites (charnockites), which should have formed at considerable depths, should now occur at such great heights is itself indirectly indicative of uplift, possibly aided by block faulting. Structural heterogeneity has given rise to step-like landscape in some parts of the country. Inselbergs, exfoliation domes and strike ridges in Archaean terrain, and plateau, mesa, butte in some of the Proterozoic terrain (particularly in the Kurnool area) are quite common.

Planation surfaces in Karnataka, Andhra Pradesh and Tamil Nadu, on a regional scale, indicate a general slope towards east, with an overall step-like topography, and most of them belong to Cenozoic era. However, those in Kerala seem to slope towards west. Table 13.1 presents the inferences drawn by different authors with regard to the surfaces they had mapped and/or recognised in different parts of south India. The correlation by different authors has been done based mainly on their relative altitudes, slopes and ages. The ages of these are arrived at based on datable deposits over them or those in an adjoining basin of sedimentation, which might have received the sediments eroded from the regions containing the planation surfaces. However, in the light of new mounting data on neotectonics (Chapter 10) and possible revision of stratigraphic data based on hiatuses recognised in different offshore basins (Chapter 12),

Table 13.1. Synopsis of published landscape morphologies and/or development histories for south India (Source: Gunnell, 1998).

Time	Chatterjee (1961)	Vaidyanadhan (1967, 1977)	King (1967)	Brunner (1968)	Babu (1975, 1981)	Demangeot (1975)	Naruse (1980)	Petit (1982,1985)	Radhakrishna (1967, 1991)	Bruckner (1988)	Klein (1997)
Quaternary		400 m (Eastern Ghats)	Rejuvenation Uplift	300-250 m (Tamil Nadu Surface)	150 m (Palghat-Madurai)	minor alterations to landscape		Various cyclic levels developed over the course of the Cenozoic and controlled in local structural base levels below the fundamental 'intra-trap' palaeosurface (1800-1900 m) e.g.1200 m (Coorg), 1000 m (Chikmagalur), 859-950 m (Mysore), 700-750 m (upper Tungabhadra), 650-550 m (lower Tungabhadra)	Cymatogenic uplifting Rejuvenation of plateaus	Pedimentation in Tamil Nadu	
Pliocene	400-300 m	700 m (Karnataka Plateau)	Dissection Uplift	450-400 m (Chitoor surface)	300 m (Palani - Tirupattur)	'Tamil Nadu cycle'	<500 m (Tamil Nadu Surf.) 700 m (Mandva Surface)		430-360 m (Newer Mysore Plateau, stage 2) 600-500 m (Newer Mysore Plateau, stage 1)	Uplift or marine Regression Regional uplift	Tamil Nadu pediment S_3
	550-450 m		Dissection	750-650 m (Punganur surface)			800 m (Mysore Surface)		Creation of Western Ghats scarp by faulting	Planation phase	Faulting and uplift of S_1 in Nilgiri and Palni (>2000 m)
Miocene	850-600 m	1000 m (Mysore Plateau)	Uplift	900-750 m (Bangalore surface)	600 m (Manantody-Kolar region)	900-600 m ('Mysore cycle')	900 m (Bangalore Surf.)		900 m (Older Mysore Plateau)		700-1000 m (Mysore surface S_2)
Oligocene	1150-900 m		Extreme Planation						Upwarp in Western Ghats	Deep Weathering	
Eocene										Planation (Indian cycle)	
Cretaceous		2000 m (Bababudan)	'High level Laterite'		900 m (Mysore Plateau)	Shevaroy level			(Nilgiri Surface)	Deep weathering and Planation	1300-1500 m Cretaceous surface S_1
Jurassic		2500 m (Nilgiri)	Gondwana Surface (Nilgiri)		1500-2700m (Shevaroy-Nilgiri)	2600 m (Nilgiri cycle)				Gondwana break-up	S_0

and different rates of erosion in different regions and geological times, these correlations will have to be revised.

Sahyadri: The broad drainage pattern, particularly emanating from the Western Ghats towards east and southeast, was thought to reflect that this part of the Peninsula might be the eastern flank of an original dome uplifted by a mantle plume. Any departure from this drainage pattern was being attributed to local tectonic causes – neotectonics or rejuvenation along old tectonic lineaments, Narmada-Tapti drainage, for instance, flowing west. Besides the well-established eastern slope of south India, recent studies have established a northern slope along the Western Ghats from Anaimalai in Tamil Nadu to Deccan Trap country in southern Maharashtra (Fig.13.1). Whatever be the tectonic model to explain this, the fact remains that the landscape owes its origin to certain amount of warping of the surfaces down due NNW. An interesting observation made about the formation of laterites over the plateau tops in the ghats and those over the coastal plains is, that the former are older than the latter (based on palaeomagnetic studies), though the former are over the Deccan Trap (Paleocene) and the latter over Deccan Trap and even the Precambrian. Another contrasting feature is that the high-level laterite reveals an anticlinal structure exactly similar to those developed over the basalt stratigraphy beneath, but the low-level lateritised surface shows a general westward slope, indicating possibly the effect of neotectonics in the region.

The conspicuous escarpment of the Western Ghats facing west is considered to have resulted from gradual recession from a position closer to the present coast. It is the headward erosion by consequent streams on the western slopes that have been mainly responsible for this. It is proposed by some that this escarpment might have been earlier much closer to the present position, the recession being much less. This is based on the inference that the heads (water divide) of many of the rivers flowing over the ghats, due southeast, do not seem to have been much beyond where they are now, with beheaded U-shaped valleys indicating this and projecting the longitudinal profiles of these rivers, headwards (backwards).

Palghat Gap is a major physiographic break along this escarpment, southwest of Nilgiri hills with a maximum width of 24 km. Whereas many kinds of origin have been attributed for its presence, the most plausible seems to be, erosion along a set of extension fractures due to a cymatogenic arch with its axis due west to east, fluvial agencies having had a major role in its formation.

Western India: In the Deccan Trap country of northern Maharashtra and southeastern Gujarat (also known as Deccan Plateau), faulting and related

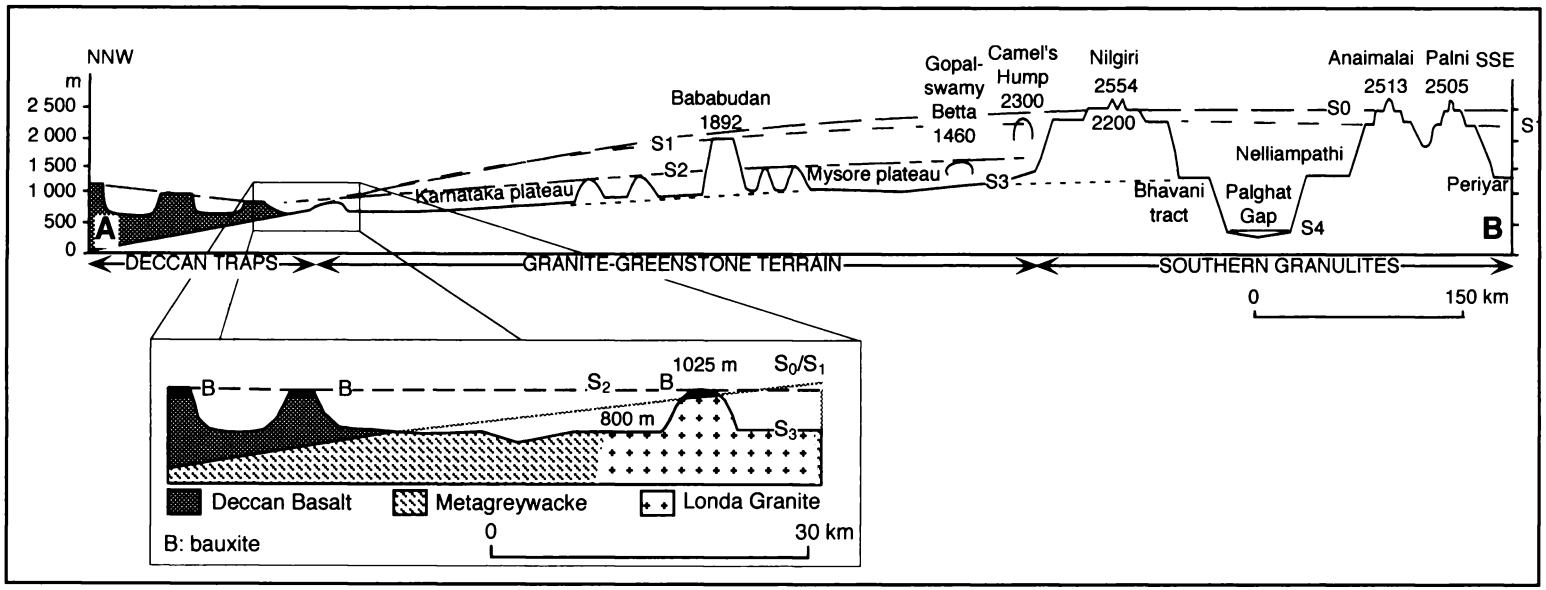


Fig.13.1. Schematic NNW-SSE sections through the upper reaches of the south Indian piedmont benchlands, parallel to the strike of the Western Ghats. S_1 and S_2 suggest post-denudational warping in a north-south direction which appears geometrically and mechanically unrelated to rift-flank uplift of the Western Ghats in the Cenozoic. Surface S_2 is reconstructed essentially on the basis of trend surface analysis and relict bauxite occurrences (source: Gunnell, 1998) (reprinted with permission from publishers of Basin Research).

vertical uplifts and subsidences are considered as the main causative factors in the evolution of the landforms, compared to the response of differing lithology to weathering agencies. The Deccan Volcanic Province also has palaeosurfaces, but in this case, one has to be careful in recognising them on a regional scale as the extensive almost horizontal lava flow tops may be mistaken for palaeosurfaces. These have been affected by faulting along Narmada Valley and sections close to Panvel in western Maharashtra. Plateaus, mesa, butte and conical hills are the common landforms in the Deccan Volcanic Province.

One of the noteworthy examples of the tectonically controlled morphology (morphotectonics) is that of Kutch (Fig. 13.2). The denudational surfaces (as the surfaces were termed then) in Kutch are displaced, but yet are traceable. They belong to different periods of Cenozoic. An interesting feature of the landscape of Kutch is the presence of first order topography where anticlines appear as hills and synclines as valleys. Table 13.2 presents the characteristics of the landscape features of Kutch.

Further north, in the Aravalli mountain of Rajasthan, occur high relief features with recognisable planation surfaces, arched up in the NW-SE direction, perpendicular to the Aravalli trend. Wherever the planation surfaces are stripped away by consequent streams and by headward erosion in lowlands or foot slopes, the underlying structure and the nature of lithology become evident. That is how in Rajasthan, in a majority of the areas, the outcrops tend to expose even complicated fold structures and the varying lithology. In stark contrast is the vast sandy plain in western Rajasthan, which presents varying dune topography, lacustrine sediments and abandoned rivers, which cumulatively are the results of neotectonics and climate.

Central and Eastern India: In Central and Eastern India, fossils to date the landforms are absent. Hence the disposition of the Vindhyan formations and Deccan Trap are considered as the basis for establishing the evolution and age of the landforms. An interesting feature is the recognition of exhumed ancient Vindhyan topography (with cuestas and hogbacks), visible now due to the removal of the overlying horizontal Deccan Trap flows. Part of the exhumation is due to natural fluvial erosion, and partly due to accelerated erosion caused by neotectonic activity in Central India.

In Chhotanagpur area of Jharkhand, and Jamda-Keonjhar region further southeast in Orissa, 3 undisturbed erosional surfaces are recognised (Fig.13.3). However, in Orissa, the surfaces occur in patches due to intense dissection. They have a range of altitude and are closely associated with laterites. These have been assigned Middle Eocene to Lower Pleistocene age based on their possible relation with unconformities in the sedimentary sequence of the adjoining Bengal basin. An attempt at establishing correlation of the surfaces

Table 13.2. Planation surfaces of Kachchh (*after* Biswas, 1974)

Planation Surface and Landscape Features	Approximate Range of Altitude (in feet above m.s.l.)	Associated Physiographic Features	Unconformity in sedimentary Sequences to which correlated	Remarks
Remnants Upper Cretaceous Landscape	1150	Isolated scattered hills of mafic intrusive rocks, highest features in landscape	Pre-Deccan Trap disconformity (Post-Bhuj) Formation	Preserved only in Central Mainland
Early Tertiary Surface (Indian cycle)	1000-1150 in N. part 900-1000 in Central part	Isolated scattered hills with accordant summits	Palaeocene disconformity (post-Trap)	Duricrusted with laterite and correlatable with terrestrial Madh Series (Paleocene)
Mid-Tertiary Surfaces	600-700 in N. part 880-850 south of Katrol fault 450-500 in Southern part	Broken chains and clusters of flat-topped hills, discontinuous ridges, plateaus and cuestas	? Post-Lower Eocene (Post Kakdi Stage)	Ferricreted surface being resurrected
Late Tertiary Surface	300-350 in Eastern part 450-500 in Central part 500-550 south of Katrol fault 150-300 in Southern and Western parts	Low ridges and flat-topped hills Terraces, ledges and saddles Residual hills and plateaus Dome hills and plateaus	Post-Miocene (Lower) (Post-Khari Series)	Not prominent where older surfaces of high relief present. Well seen in areas of low relief - E & S parts
Early Quaternary Surface (Kutch cycle)	300-400 in N. part 100-150 in coastal areas	Extensive plains-sandy wasteland, rocky plains, and cultivated lands	Post-Pliocene (Post-Kankawati Series)	Most dominant surface in Kutch, covered by Recent sediments. Locally calcreted
Late Quaternary	100 above valley floor 25-30 above valley floor 3-5 below valley floor	Terraces in deeply incised valleys	Quaternary uplifts	Miliolite deposit Rubble and clay deposits Rubble deposits

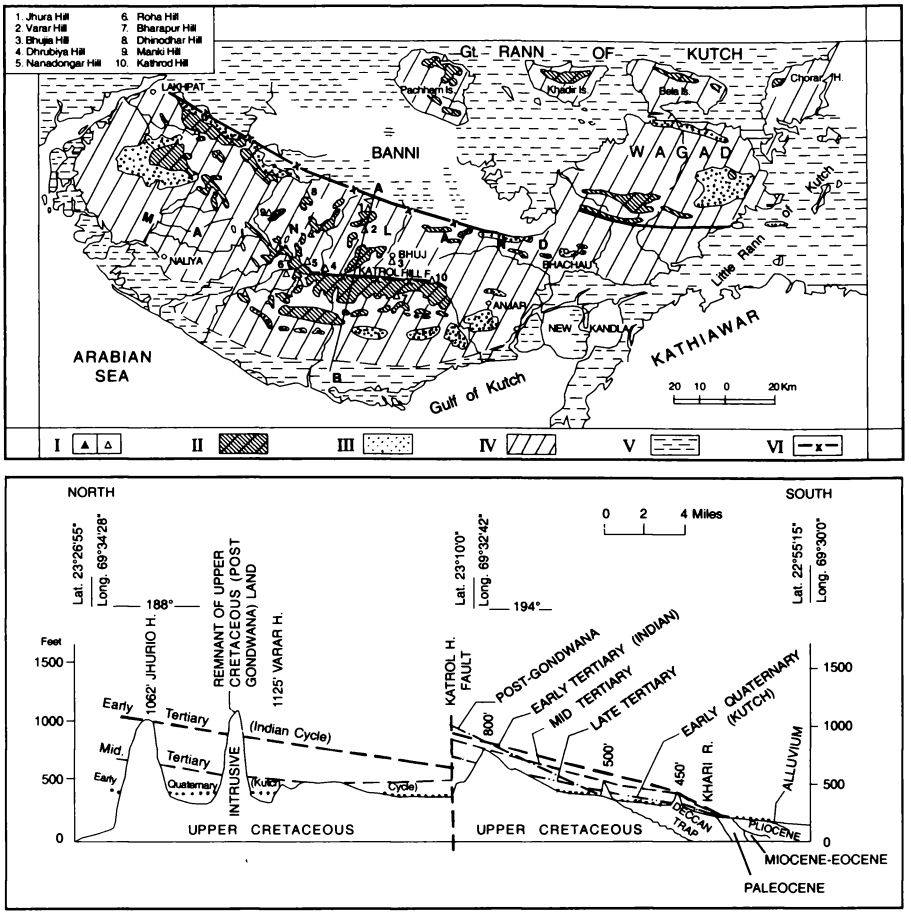


Fig.13.2. (**a**) Generalised morphological map of Kutch showing cyclic denudational surfaces. **I**- Relics of Upper Cretaceous/Early Tertiary (Indian Cycle) landscape. **II** - Mid-Tertiary land suface. **III** - Late Tertiary land surface. **IV** - Early Quaternary land surface (Kutch cycle). **V** - Depositional plains. **VI** - Fault. (**b**) Profile across Kutch mainland showing cyclic landsurfaces (along line AB in Fig.13.2a) (after Biswas, 1974; reprinted with permission from IJES).

in Jharkhand clearly showed that the surfaces do not exist at the same comparable altitudes above mean sea level in all the adjoining regions (Table 13.3). This is partly due to the fact that the surfaces have natural inclination, besides the possibility of minor cymatogenic arching of these locally.

In spite of being located in a region that has been subjected to repeated uplift, intense dissection and extensive erosion, mainly due to fluvial processes, it has been possible to trace the evolution of the landscape in the north-eastern region of India also and recognise regional surfaces both in the Foothill Himalaya and the plains, south of Shillong Plateau (Fig.13.4). The Shillong-Mikir plateau is a very conspicuous landmass. Erosional surfaces within this plateau range from Early Paleogene to Late Neogene, the highest surface being

Table 13.3. Tentative correlation of palaeosurfaces of south Bihar, i.e. present Jharkhand (after Mahadevan, 2002, p.96)

Geological Time		Global Classification King (1962) (* 1)	Madhya Pradesh Dixey (1974)	Keonjhar Ramana Rao and Vaidyanadhan (1974)	Bihar		
					Dunn (1939,1941) (* 3)	Evans (1976)	Mahadevan (1999)
Quaternary	Holocene	Congo surfaces Coastal Plain surface Gorges and waterfalls of rejuvenated river systems	Quaternary cycle (Gorges and water-falls)	Alluvium - detrital and *in situ* laterite	Late Tertiary: Dhalbhumgarh surface		Gorges and waterfalls Subarnarekha Terrace < 150 m asml
	Pleistocene		Marble rock gorge Narmada valley	Jamda surface (400-520 m)			Santhal Pargana surface <150 m asml
	Pliocene	Valley excavation cycle			Middle Tertiary: Ranchi plateau	Kodarma surface (500-150 m)	Kodarma surface (300-150 m)
Miocene	Late					Lower Ranchi surface (550-425 m)	Lower Ranchi Surface (600-300 m)
	Middle			Naomundi surface (660-600 m)		Upper Ranchi surface (800-600 m)	Upper Ranchi surface (800-600 m)
	Early						
	Oligocene	Indian cycle (extreme planation of plateau India)	Jabalpur surface (400-300 m) (post-Deccan Trap)	Kiriburu surface (900-825 m)	Early Tertiary: Netarhat surface	Netarhart surface (1170-600 m) (post-Deccan Trap)	Netarhart surface (1170-1000 m) (post-Deccan Trap surface
	Eocene						
Cretaceous	Late to Middle	African surface or Moorland surface	Cretaceous peneplain (sub-Deccan Trap surface) (* 2)				Palamau surface (post - Lameta)
	Lower	post-Gondwana surface					post-Rajmahal Trap surface
Jurassic	Upper to Middle	Gondwana surface	Bhander surface (700-600 m)				Rohtas surface = Sub-Rajmahal Trap surface (600-450 m)

(* 1) Compiled from Holmes, 1965, p.605 and Dixey (1974); (* 2) Corresponding Dhupgarh surface of Pachmarhi area, Venkatakrishnan (1984) and Pre-Deccan Trap surface of Choubey (1971); (* 3) Surface not correlated with other surfaces

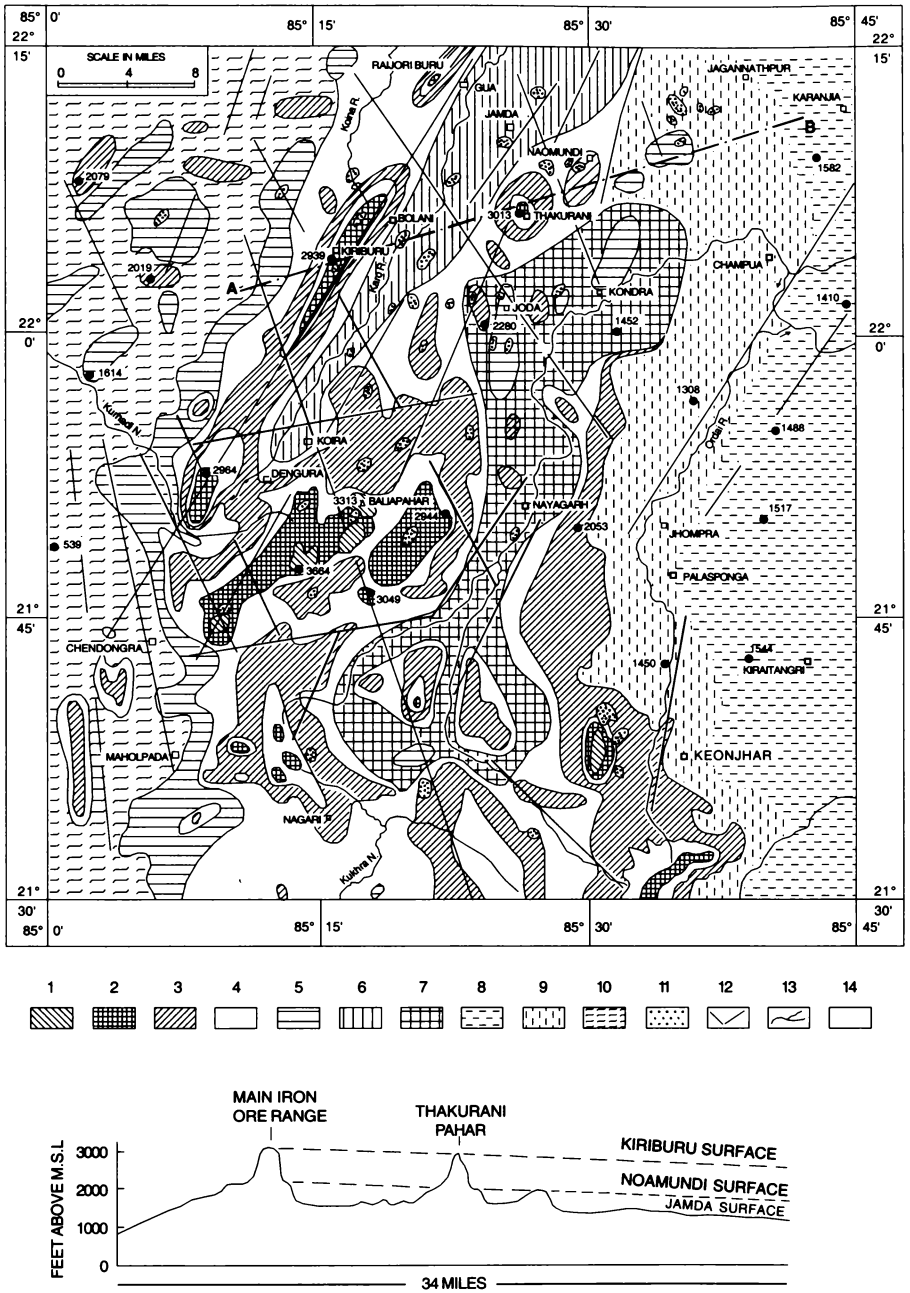


Fig.13.3. Geomorphic map of Keonjhar region (after Ramana Rao and Vaidyanadhan, 1974). **1**- Remnants of Primary cycle. **2** - Kiruburu Surface. **3** - Noamundi Surface. **4** - Dissected relics of higher surface. **5** - Flat areas of the Jamda Surface. **6** - Jamda-Koira valley. **7** - Nayagar Valley. **8** - Champua-Keonjhar upland plain (Keonjhar pediplain). **9** - Pediments. **10** - Undulating western low lands. **11** - Lateritic patches. **12** - Prominent lineaments. **13** - Drainage lines. **14** - Spot heights in feet above MSL. (Reprinted with permission from IJES).

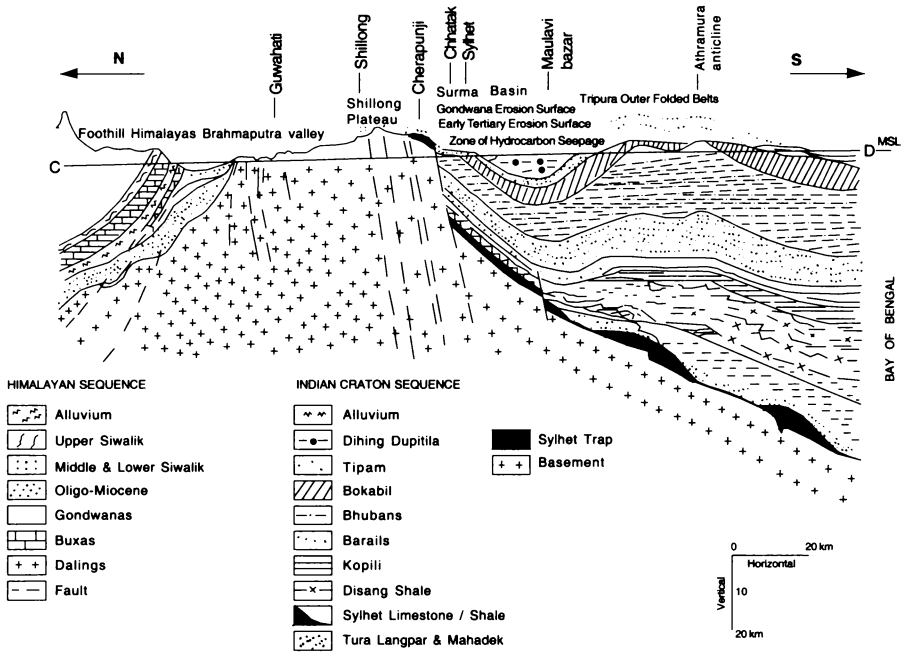


Fig.13.4. A North-South cross-section from the Himalayas to the Bay of Bengal (after Desikachar, 1999) (reprinted with permission from Pilgrim Publishing, Varanasi).

around 2000 m. North of this plateau the surfaces occur at lower elevations. This change in the elevation is accounted because of northerly tilt of the plateau resulting due to overriding movement of Himalaya from the north. Five distinct surfaces have been recognised between Mikir and Naga Hills, correlatable with known unconformities over the basement. Neotectonic activity along the pre-existing faults has modified the landforms of this plateau due to close proximity to the Himalaya.

In Orissa, in an approximately E-W direction over the Eastern Ghats, two upland plateaus (surfaces) occur at different levels (Fig.13.5) with a peneplain on the east. Most of the bauxite is found in parts of the highland plateaus, e.g. Panchpatmali. It has been envisaged that the different levels of erosion may be indicative of differential erosion and possible vertical movements.

Karst Landscape

These are few and far between in the country. In the Proterozoic Bhander Limestone of the Vindhyan Supergroup, both surface and subsurface karst landforms are reported. Surface ones include karren, solution basins, pavements, natural bridges and sinkholes. Subsurface landforms include caves, cave deposits, terra rosa, rock falls etc. These have formed due to differential erosion

by rivers and response of lithology to climate changes. Extensive development of karstic landscape is seen around the Rewa-Maihar and Satna areas. Karst topography is also common in parts of Chattishgarh basin. Caves with stalactites and stalagmites in Kotomsar-Gupteshwar area is reported from Indravati basin further south. A cave of almost 19 km long, perhaps the longest in Asia, has been reported near Jowai in Jaintia Hills district of Meghalaya, in Sylhet Limestone of Eocene age. Obviously it is facilitated by differential dissolution of the calcareous parts of the sediments on account of its topography and copious rainfall.

Bornhardt

Bornhardt is a domal shaped landform with altitude above 300 m from ground level surrounded by a pediplain, which reflects partly the effect of climate in arid and semiarid regions. These are common in parts of Karnataka and Andhra Pradesh and are usually made up of granites, acid gneisses and migmatites and rarely of quartzites. Though there are many hypotheses to account for these, deep chemical weathering, exfoliation due to unloading resulting in sheeting are among the common origins attributed. It may be of interest to note that some of the famous forts of the kings in the past, particularly in south India, are located over bornhardts.

Dunes

A variety of landforms caused essentially by wind are to be seen in Thar desert in western Rajasthan (Fig.10.3). The dunes of various shapes – barchans, parabolic dunes, transverse dunes, longitudinal dunes, sand sheets etc. result from wind action, the controlling factors being availability of sand, direction and velocity of the wind, obstacles present and arid to semiarid climate. In the desert there are also erosional landforms like ergs, hammada, deflation hollows etc. There are dunes along the coasts and banks of many rivers.

Badlands

Another interesting landform occupying tens of square kilometres in parts of Peninsular India, mainly in M.P./U.P. in Chambal Valley, in Mahi, Sabarmati and Narmada valleys in Gujarat and also in parts of coastal plains are the 'badlands.' These have developed on unconsolidated sediments, namely of sands, silts and clays. Strong seasonality with extended dry periods with little or no vegetative cover and tectonic uplifts contribute significantly in the formation of badlands. In the badlands active stream channels are frequent, channels are closely spaced, and the drainage density is high. It is also well known that

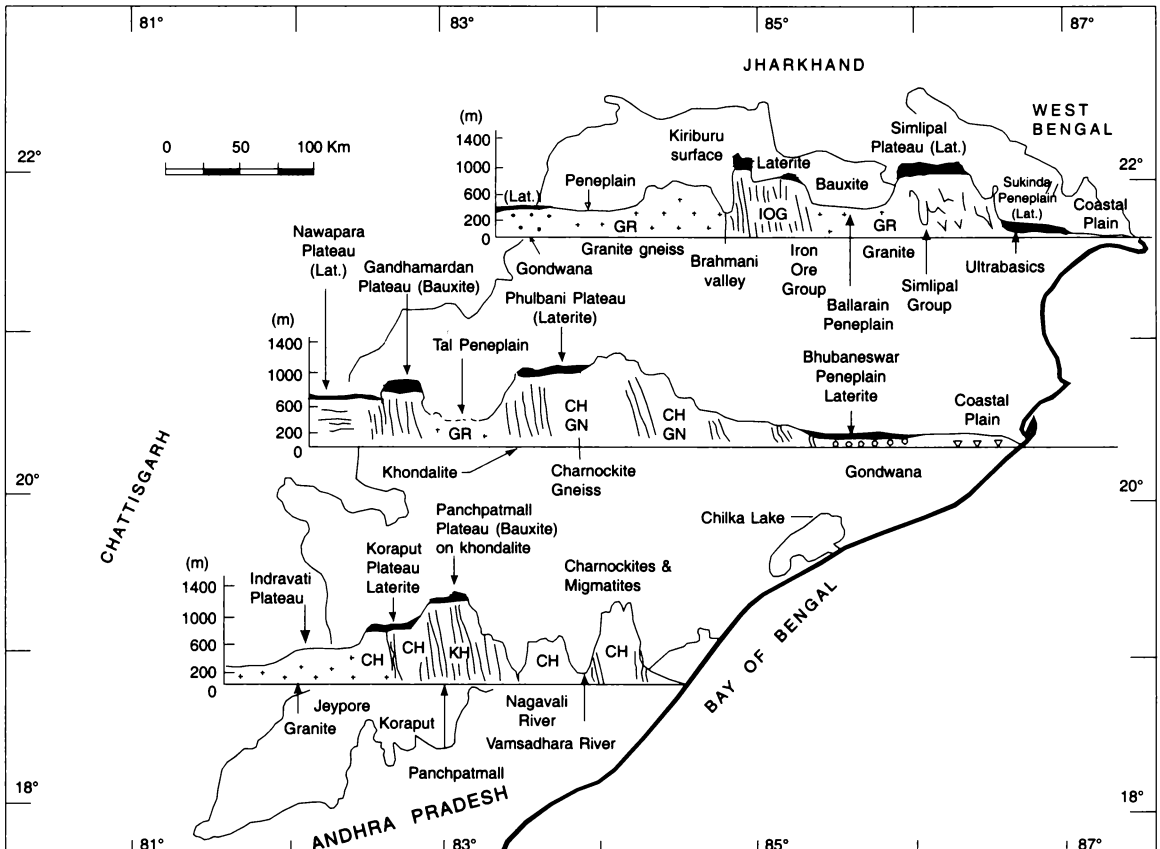


Fig.13.5. Physiographic variation in the southern, central and northern segments of Orissa (after Mahalik, 1998).

overgrazing, and wrong agricultural practices in terrains of the type mentioned above can also hasten formation of these land types. Knife-edge interfluves and earth pillars are commonly met within badlands.

Drainage

Whereas epeirogeny, cymatogeny and extended periods of erosion bring about different types of landforms, the patterns of drainage in different parts reflect lithology, structure, slope, tectonics and climate depending upon the location of the area. It will be seen that the ultimate pattern will be guided by the dominance of one or two of the above factors over others. For example, in south India, the major drainage is towards southeast in conformity with the general slope of the ground. The rivers discharge into the Bay of Bengal, as a result of a possible tilt during post-Eocene, though in some sections of their courses the rivers may be controlled by the structure. The west-flowing rivers along the coastal belts discharging into the Arabian Sea are mainly consequents, though some of them, by headward erosion had captured the headwaters of east flowing rivers as in the case of Sharavathi, Kali Nadi, etc. The two major rivers Narmada and Tapti are essentially structure controlled and flow west.

Further north of Narmada is a linear tract of alluvial plain formed by the deposition of thick fluvial sediments during Quaternary within the Cambay rift graben. The drainage network of this plain shows excellent control of sub-surface structural features of the Cambay basin (Fig.13.6). Recent geo-morphological studies combined with stratigraphic studies on the exposed Quaternary sediments here have shown that neotectonics and sea level changes have played a major role in shaping the landscape of this plain.

In Rajasthan, ancient abandoned channels of Saraswati and Drishadvati, often mentioned in ancient Vedic literature, have been recognised from satellite data (Fig.13.7). In this case the changes are supposed to have been brought about mainly due to climatic changes, though other factors might have had minor roles to play. As far as the modern rivers in the Peninsula are concerned their present day characteristics are very much controlled by varying discharges during high-magnitude floods and also the nature of the sediment load carried and distributed.

Coastal Plains

Sea level fluctuations, geomorphic processes and reactivation along regional/local faults during Quaternary have been largely responsible for the disposition and nature of coastal landforms. These have played varying roles in different parts of the coasts. The Ranns of Kutch, the Saurashtra coastline,

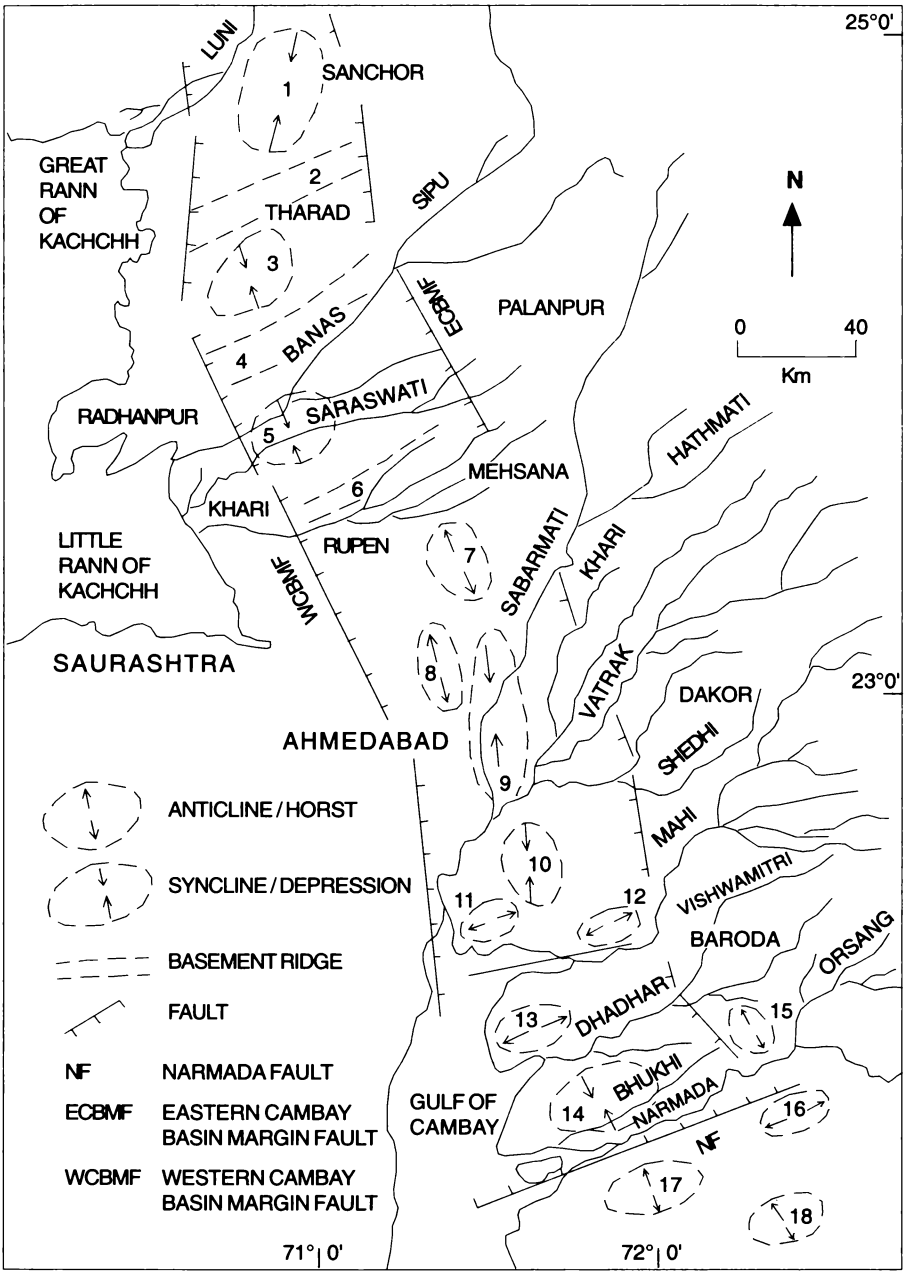


Fig.13.6. Subsurface structural features superimposed over the drainage map of South Gujarat. **1** - Sanchor depression, **2** - Tharad ridge, **3** - Paiyak depression, **4** - Diyodar ridge, **5** - Patan depression, **6** - Unhawa ridge, **7** - Mehsana horst, **8** - Kalol high, **9** - Gandhinagar basin, **10** - Tarapur depression, **11** - Cambay high, **12** - Kathana anticline, **13** - Dhadhar anticline, **14** - Broach syncline, **15** - Atali anticline, **16** - Jhagadia anticline, **17** - Ankleshwar anticline, **18** - Talodra anticline. Subsurface data after Mathur et al. (1968), Biswas (1987), Kaila et al. (1990) and Roy (1990). (after Maurya et al. 2000).

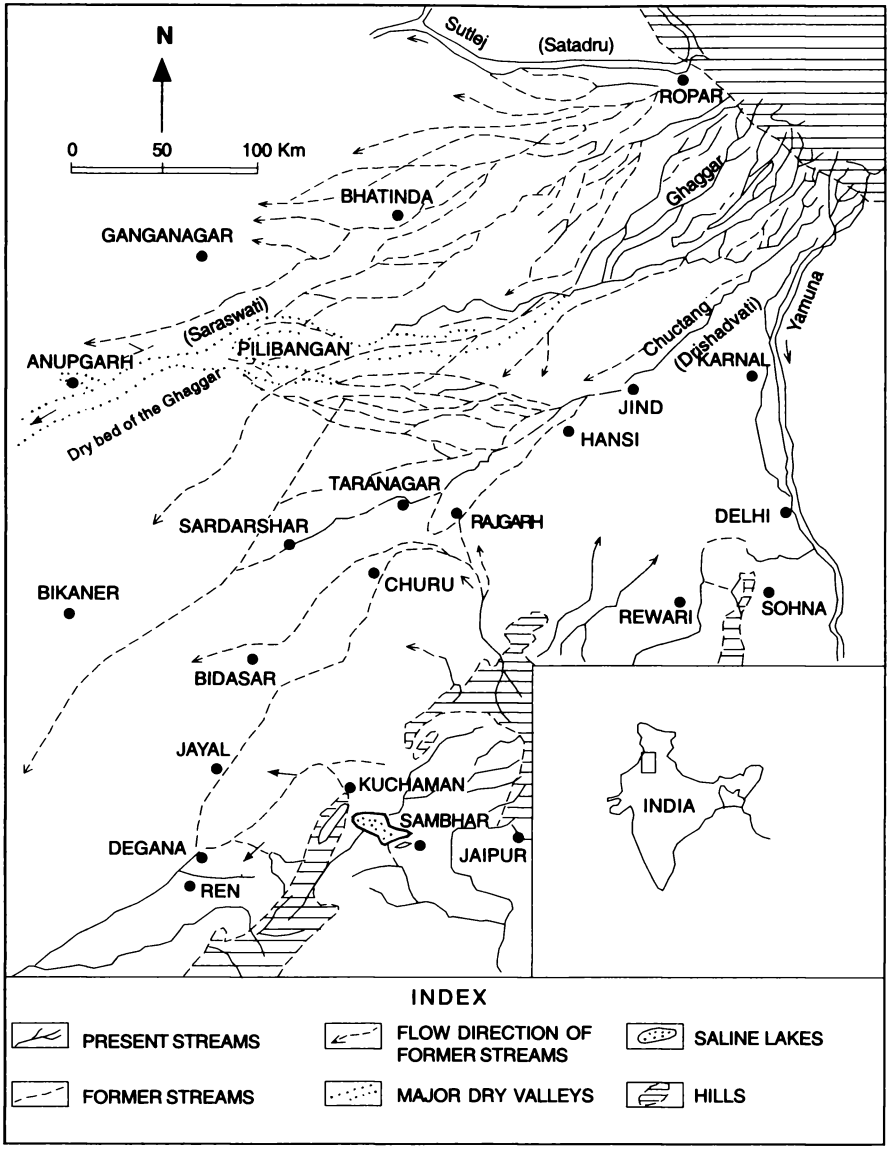


Fig.13.7. Major palaeochannels in Rajasthan and adjacent areas (after Amal Kar, 1995).

the Gulf of Khambat (Cambay) and the south Gujarat coast show different types of landforms because of the above. The same can be said of the evolution of coastal landforms further down along the west coast from Maharashtra to Kerala through Karnataka. On the other hand, the coastal plains all along the east coast of India are interrupted by a number of deltaic plains. The deltas have different sizes and shapes (Fig.13.8) controlled by a number of factors. These include the nature of morphology and lithology of the drainage basin, gradient and hydrodynamics of the river, precipitation over the drainage

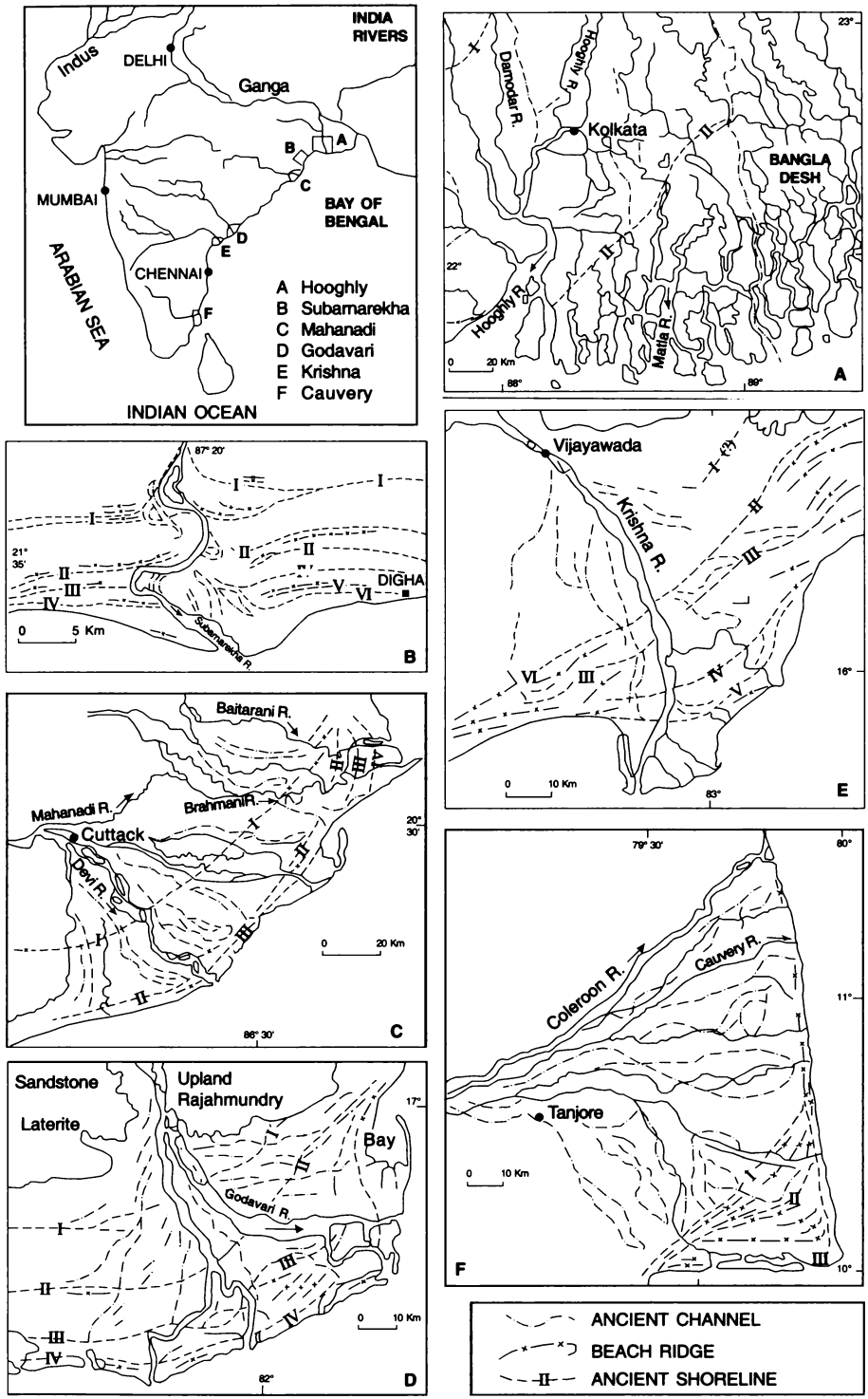


Fig.13.8. River deltas of India showing major ancient chanels, beach ridges and possible stages of progradation (after Vaidyanadhan, 1991).

basin, nature of the continental shelf, effectiveness of the longshore currents, stability of the basin etc. The stages of evolution of each of the deltas are well documented particularly based on the study of aerial photographs and satellite imagery.

EXTRA-PENINSULAR INDIA

It is well known that the overall shape of the landforms is controlled by factors like tectonics (structure), climate, lithology and geomorphic processes. Himalayan landscape is no exception, except that the degree of effectiveness of each of the above depends on where one is located within this large and extensive domain. To put it in a nutshell, it is the major thrusts that have brought about the significant topographical/altitudinal contrasts in the landscape of the Himalaya (Fig.13.9). It is unlikely that all the designated thrusts are continuous lines of displacement along the Himalayan terrain from the northwest to the northeast. They are only made up of detached sets of faults, which have brought the initial variations in relief along and across the Himalaya. Then come the processes that erode and/or deposit leaving behind their characteristic landforms. It could be glacial and lacustrine (Fig.13.10) as in parts of Ladakh, or it can be glacial, glacio-fluvial and fluvial as illustrated in Kali river basin of Pithorgarh district, Uttaranchal (Fig.13.11). The landscape, particularly in a major part of the Himalayan terrain, is always subject to occasional neotectonic activity, a phenomenon relatively not so common in Peninsular India.

Glaciation

In Peninsular India major landscape shaping is caused by epeirogenic activity, followed by cymatogenic upwarps and downwarps and action of geomorphic processes – fluvial, aeolian, marine etc. In Extra-Peninsular India, however, orogenic movements were followed by intermittent uplifts resulting in substantial altitudinal relief. This was followed by the effect of the monsoons, and formation of snow and glaciers. Changes in season brought in accumulation and ablation in this terrain, giving rise to many minor landforms, caused due to the action of glaciers and rivers (Fig.13.11).

Whereas in the northwest Himalaya the effect of glaciers is profound, the same is not the case in northeastern Himalaya. This may be partly due to altitudinal differences and also partly due to the varying role of the geomorphic agents of erosion and deposition, besides climate. In the northwest it is glacial and fluvial. In the northeast it is essentially fluvial. A four-tier terrace system of central and lower stretches of the Tista River in the Sikkim-Darjeeling Himalaya corresponds to an equal number of large-scale terrace surfaces in the

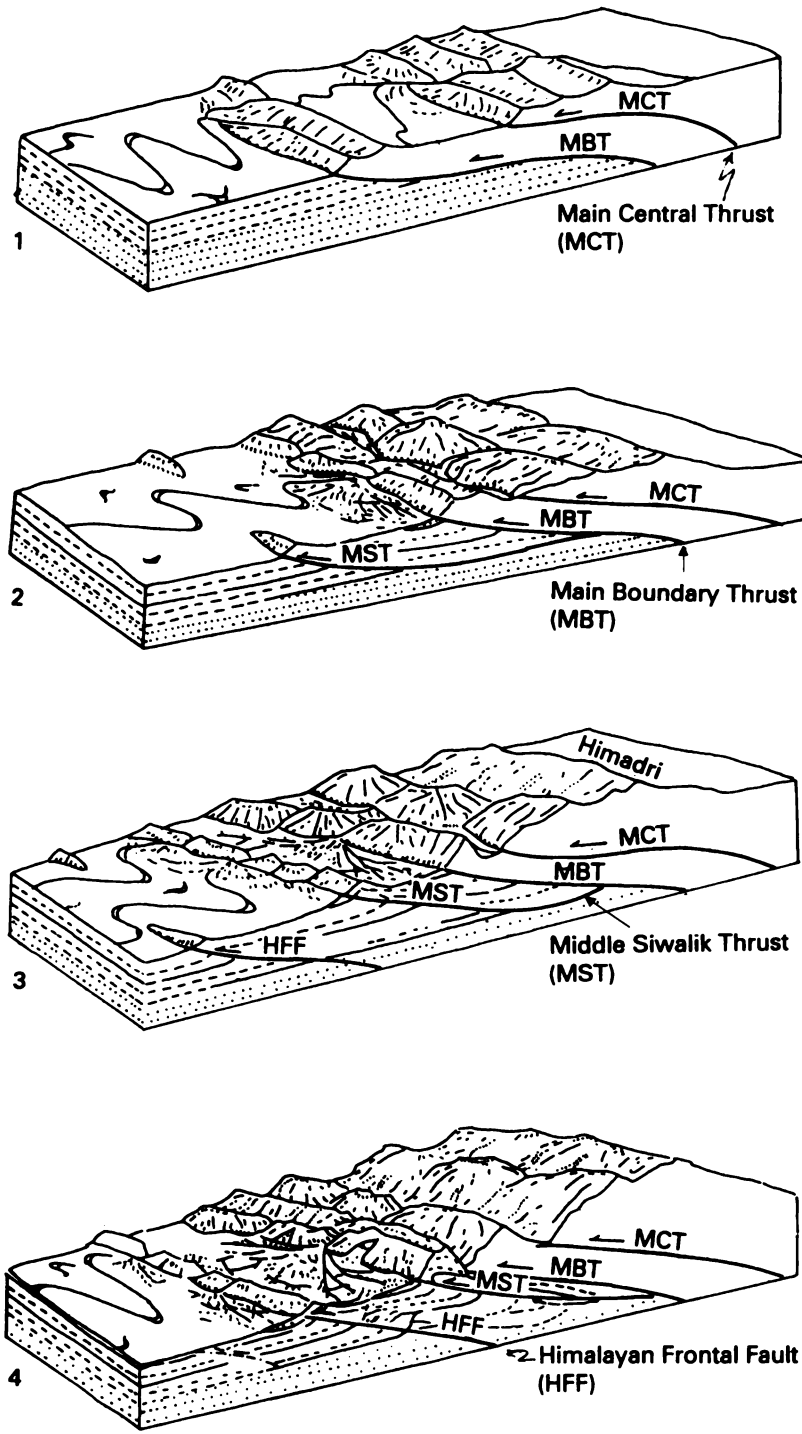


Fig.13.9. Evolution over a long period of time of the four major thrusts defining the boundaries of the Himalayan terranes (source: Valdiya, 1998, p.97). (Published with arrangement with Universities (Press) Private Limited).

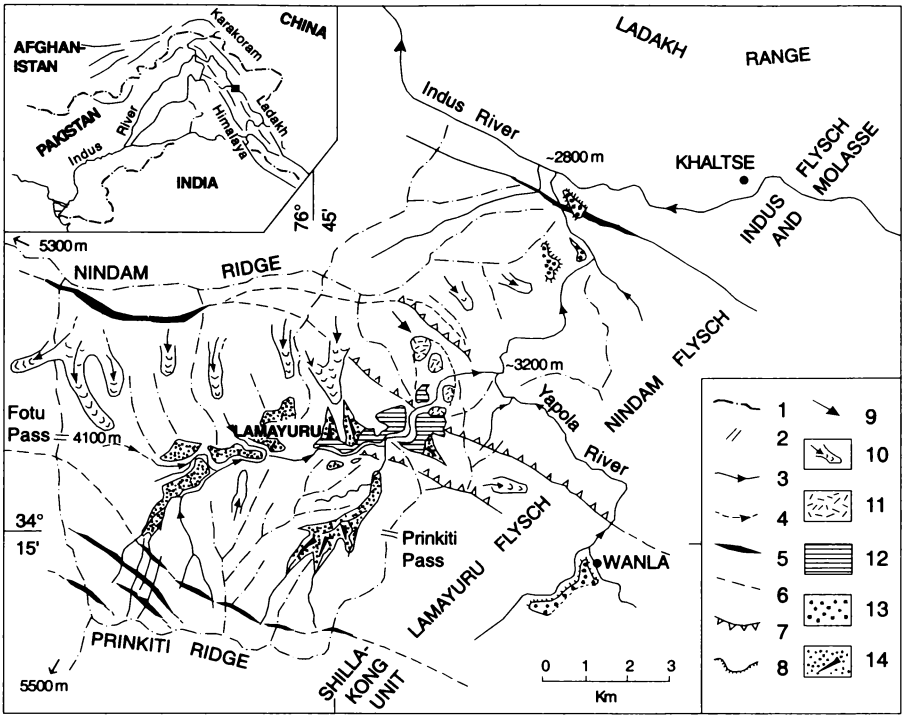


Fig.13.10. Geomorphological and geological setting of the Pleistocene Lamayuru lake. Most slopes are covered by frost-shattered debris. The strike of the geologic outcrops is controlled by the Indus Suture Zone. *Inset:* Location of the study area. **1** - Ridge, **2** - Pass, **3** - Perennial stream, **4** - Intermittent stream, **5** - Serpentine lens, **6** - Geologic contact, **7** - Monoclinal (hogback) scarp, **8** - Alluvial/lacustrine scarp, **9** - Direction of debris tongue which dammed the Lamayuru catchment, **10** - Solifluction tongues (occurrence favoured by the presence of serpentine lenses), **11** - Brecciated landslide material, **12** - Lacustrine silts, **13** - Prelacustrine alluvial gravels, **14** - Late lacustrine fanglomerates, grading to the top of the lake. (after Fort et al. 1989). (© 1989; reprinted with permission from Elsevier).

adjoining piedmont region. The terraces show a chronological sequence of development. Thus it is seen that the Quaternary landform development and depositional cycles in the Himalaya and in the piedmont region are interdependent responses of episodic uplifts and progressive shifts of the mountain front.

Drainage

In Himalaya there are no large plateaus of the type met with in Peninsular India. Even if they existed, they have been highly dissected and transformed into numerous mountains with sharp interfluves and high peaks, some of them capped by snow. The drainage pattern has been mostly controlled by lithology

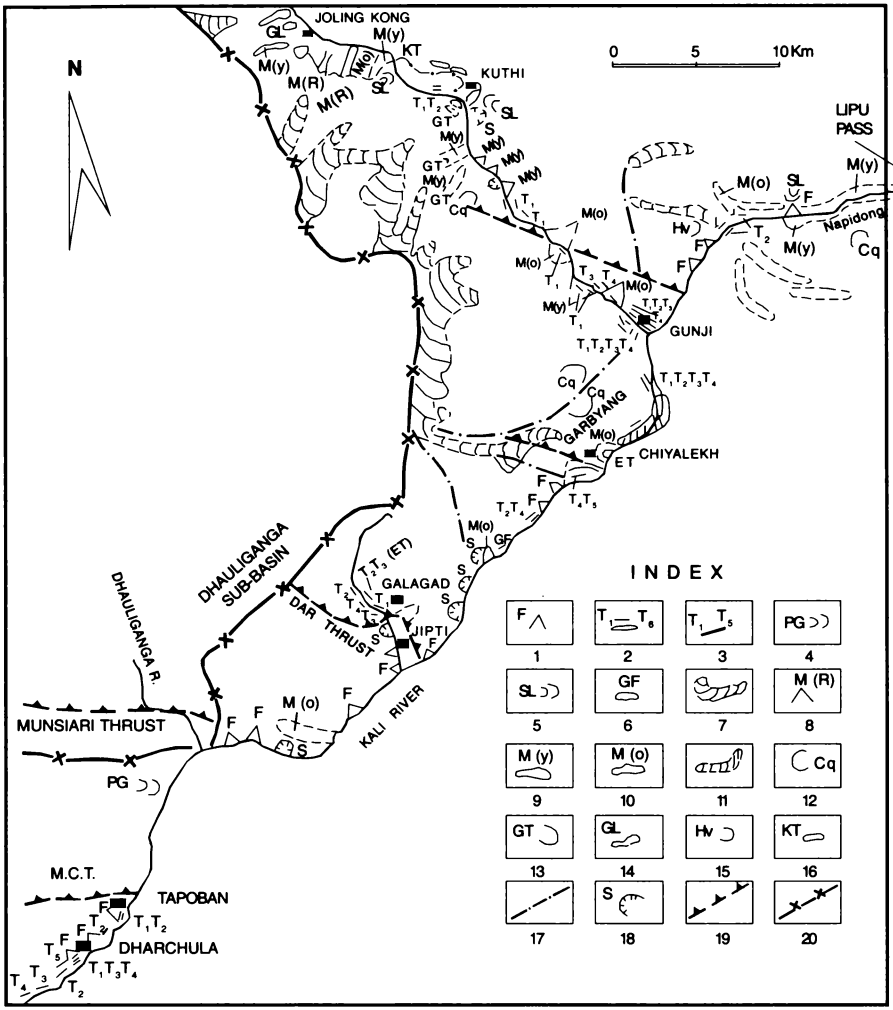


Fig.13.11. Quaternary geological and geomorphological map of Kailash-Mansarovar route, Pithoragarh district, Uttarakhand. **1** - Alluvial /Colluvial fan, **2** - Fluvial terraces (depositional), **3** - Fluvial terraces (erosional), **4** - Periglacial deposits, **5** - Solifluction lobes, **6** - Glaciofluvial terraces, **7** - Active glaciers, **8** - Recent moraines, **9** - Younger moraines, **10** - Older moraines, **11** - Varved clay, **12** - Cirque, **13** - Glacial trough, **14** - Glacial lake, **15** - Hanging valley, **16** - Kame terrace, **17** - Aretes and horned peaks, **18** -Areas of active slides, **19** - Thrust, and **20** - Sub-basin boundary. (after Rajesh Kumar and Singh, 2001).

and structure except where some of the major rivers, being antecedent, cut right across the ranges with high vertical sides forming stupendous gorges. The present day rivers flowing in this terrain have extreme variability in discharge and sediment load. Earthquakes and landslides have a great impact on these rivers.

INDO-GANGETIC-BRAHMAPUTRA PLAIN

Sandwiched between the mighty Himalaya in the north and relatively subdued topography in the south is the Indo-Gangetic Plain, extending from Punjab in the west to Bengal in the east; further east is the Brahmaputra Plain in Assam and Arunachal Pradesh. Though the Ganga Basin got initiated in Paleogene, consequent on the uplift of the Himalaya, the sediments of the plain are mostly of Quaternary age. In an earlier Chapter (10) the morphology and content of this vast plain has been dealt with in detail.

Planation (Aggradational) Surfaces

Planation surfaces are not only confined to Peninsular India, they are met with even in alluvial plains of Western India. The only difference is that in the former case most of them are erosional in character, whereas in the latter they are mostly aggradational. Figure 13.12 presents two profiles of the planation surfaces. The first one shows the aggradational surface together with terraces, where cut across by rivers. The second one is also aggradational but its geometry is largely controlled by tectonics at the NNE end and sea level changes at the SSW end. Table 13.4 presents the geomorphic units in Punjab-Haryana-Rajasthan Plains. They are essentially aggradational plains. The geomorphic development of alluvial plains in this part is related to climatic and base level changes, in response to sea level changes.

Table 13.4. Geomorphic units of Punjab and Haryana-Rajasthan plains (source: Ghosh, 1992, p.18)

Punjab Plain		Haryana-Rajasthan Plain	
Geology	Landforms Units	Geology	Landform Units
Present Alluvium	Fans, channel fills, braids coalesced alluvial fans as large peneplain with calcrete soil on top	Present Alluvium	Sandy peneplain, heaps ridges (deposits of aeolian type)
Younger Alluvium (T1)	Present floodplain (depositional)	Younger Alluvium	Present dune, wadi, sometimes playa (deposits affected by aeolian processes and flash floods)
Older Alluvium	Large terraces-regional peneplain (deposits of fluvial type, fan setting)	Older Alluvium (T2)	Predominantly pediplain (initially larger)
Upper Siwalik, Mesozoic shelf deposit	Buried peneplain	Aravalli-Delhi Fan, Mesozoic shelf deposit	Inselberg, mesa, discontinuous hills, buried pediplain

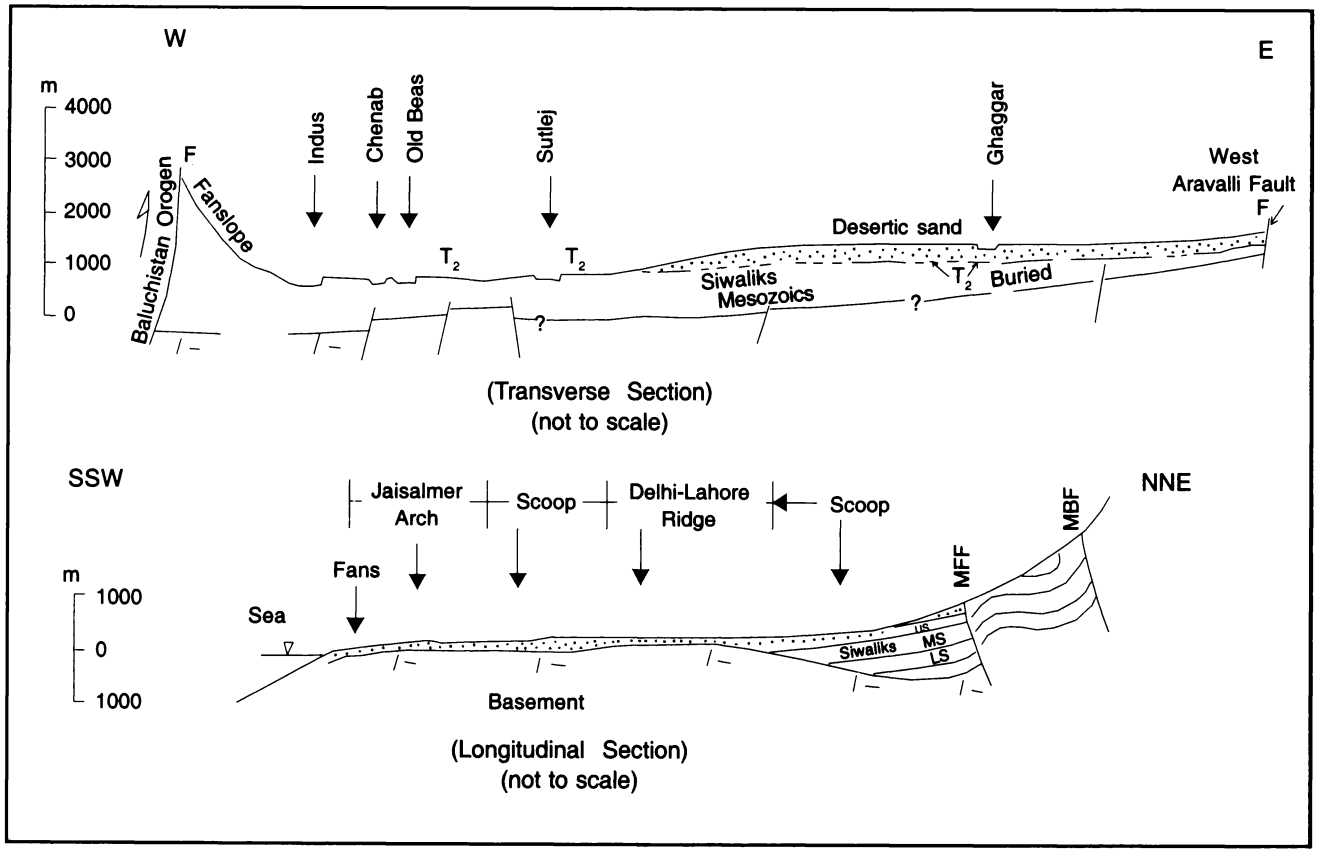


Fig.13.12. Generalised cross-section of the planation surface (longitudinal and transverse) (source: Ghosh, 1992) (reproduced from Gangetic Plain: Terra Incognita).

The evolution of the major landscape further east in the Ganga Plain is essentially shaped by fluvial processes, with sediments being brought in from the northern lofty Himalaya and the southern peninsular shield by numerous rivers, more from the north and less from the south. Periodic uplift mainly at the Himalayan Frontal Fault, results in the formation of alluvial fans and cones of very large dimension very close to the foothills. In the plain are a number of terraces formed both above the riverbed and close to it. Some of these may owe their origin to variation in sea level, though the sea, namely Bay of Bengal, is too far away. Figure 13.13 is a simplified, idealised geomorphic map depicting the major features one comes across in the Ganga Plain.

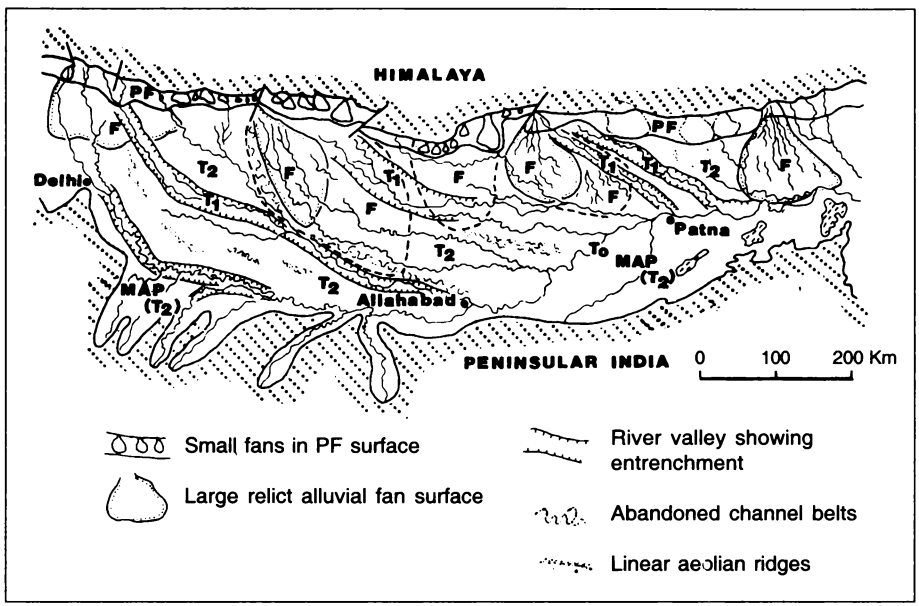


Fig.13.13. Schematic geomorphic map of Gangetic plain showing major geomorphic features. T_2 - Upland terrace surface, MAP (T_2) - Upland terrace surface of Marginal Alluvial Plain, F - Large relict alluvial fan surface, PF - Piedmont fan surface, T_1 - River valley terrace surface, T_0 - Active flood plain (source: Indra Bir Singh, 1992, p.5). (reproduced from Gangetic Plain: Terra Incognita).

Drainage

A study of part of Gangetic Plain using satellite imagery reveals numerous abandoned channels and channel belts (Fig.13.14). Some channels migrate laterally, some suddenly cut across interfluves to join other streams. Oxbow lakes and meander scars are evidences of migration; in some cases there have been lateral planation piracies as well. Upstream migration of confluences is considered to be a consequence of a decrease in carrying capacity of major rivers. Sea level rise during Pleistocene-Holocene led to the base level changes

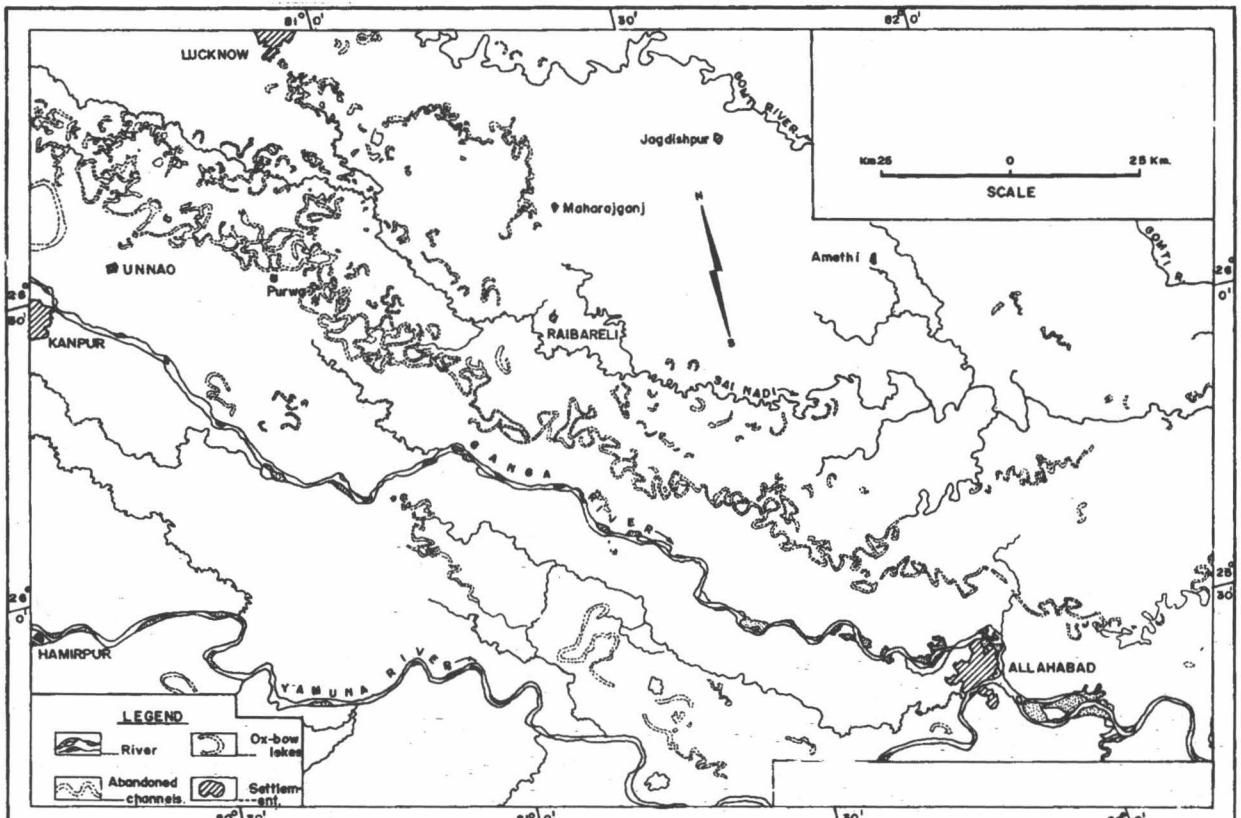


Fig.13.14. Traces of abandoned channels and channel belts in Ganga-Gomti interfluve (interpreted from Landsat-5, scene nos.143-041, 145-042, 144-041 and 144-042) (source: Tangri, 1992). (reproduced from Gangetic Plain: Terra Incognita).

and an overall reduction in the hydraulic gradient of the river systems and also of choking up of the rivers.

Further east in Brahmaputra Plain one finds almost similar features, but tectonic control of the fluvial morphology is more common, situated, as it is between the rising Himalaya and tectonically repeatedly affected Shillong and Mikir plateaus. Brahmaputra river is an aggrading river and has an interlacing (braided) channel pattern. In spite of its very low gradient in Assam its erosive power is enormous and during the recent years it has completely destroyed many towns. It has the largest river island in the country at Majuli in upper Assam, which is 90 km long and 20 km wide.

It is thus summarised that the morphology of the Indian subcontinent is controlled by the following major causative forces/agents, acting over the landmass, approximately in the sequence presented here.

1) Dismemberment of Gondwanaland and migration of Indian Plate (vol.1, Fig.2.6, p.79) for a long period of time over about 50° Latitude.
2) During this process, parts of it got separated and the major part of it happened to move over hotspots – Reunion in the west and Kerguelen in the east (Fig.9.1).
3) Rifting took place followed by faulting and submergence of part of the Indian mass in the west leading to the formation of Arabian Sea. In the east, Bay of Bengal became a large repository of sediments flowing in from the north and west (vol.1, Fig.1.10).
4) Peninsular India went through epeirogenic movements followed by some amount of block faulting and then prolonged erosion leaving behind step-like surfaces. Similar features are present all over the shield part, though affected locally (Table 13.1).
5) The subduction of Indian Plate below the Asian Plate gave rise to Himalaya, and raising it intermittently (vol.1, Fig.4H-4).
6) Climatic changes led to a canopy of snow and glaciers over parts of the Himalayan mountains, aiding step-by-step formation of landforms connected with the processes operating here (Figs.13.10 and 13.11).
7) Fluvial agents aided in the erosion of enormous amount of sediments and deposition in a foreland basin to the south of the uplifted Himalaya leading to the formation of the Indo-Gangetic-Brahmaputra Plain, with attendant landforms above and along the floodplains (Fig.13.13).

Thus the Indian subcontinent has come to take the present form as a result of tectonics and action of exogenic agencies over a long period of time, perhaps from around Jurassic to the present day.

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Steeply dipping purple siltstone shales of Thango Formation succeeded by Muth quartzites belonging to Ordo-Silurian to Devonian in the foreground. The river Tsarp Lingti Chu flows through an earlier U-shaped glaciated valley, joining the Zanskar river further down (Courtesy: S.V. Srikantia)

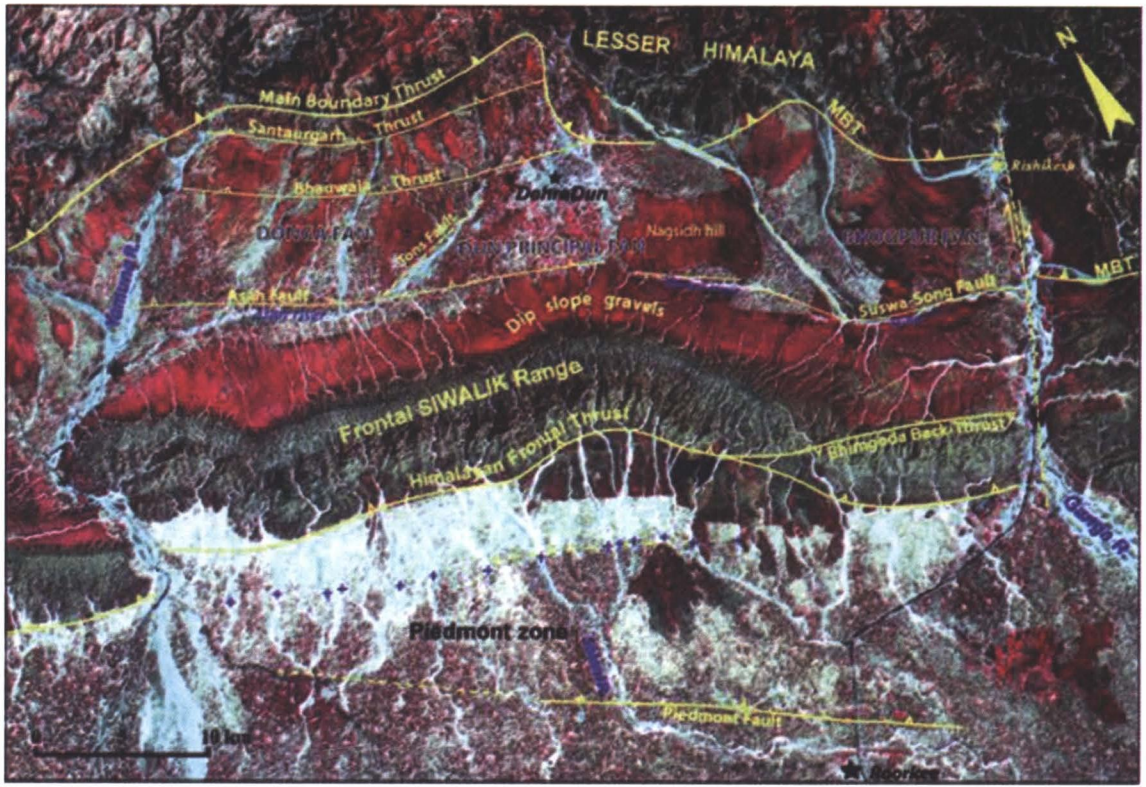
Intense folding of strata belonging to the Lilang group (Triassic, dominantly a carbonate sequence) near Sarchu River in the Spiti Himalaya. In the foreground can be seen the dissected river terrace, and scree from the hills (Courtesy: O.N. Bhargava).

Recumbent folding in Triassic limestone of East Zanskar Tethyan belt, Ladakh, Jammu and Kashmir (Courtesy: S.V. Srikantia).

Thick coal seam in Barakar Formation, Rajmahal coalfield, Jharkhand. Exposure of Lalmatia II Top coal seam (4.9 m) of Barakar Formation overlain by carbonaceous shale (0.7 m) and Barakar Sandstone (1.5 m) in Lalmatia Open cast mine, Hura coalfield, Rajmahal basin (Courtesy: M.P. Singh).

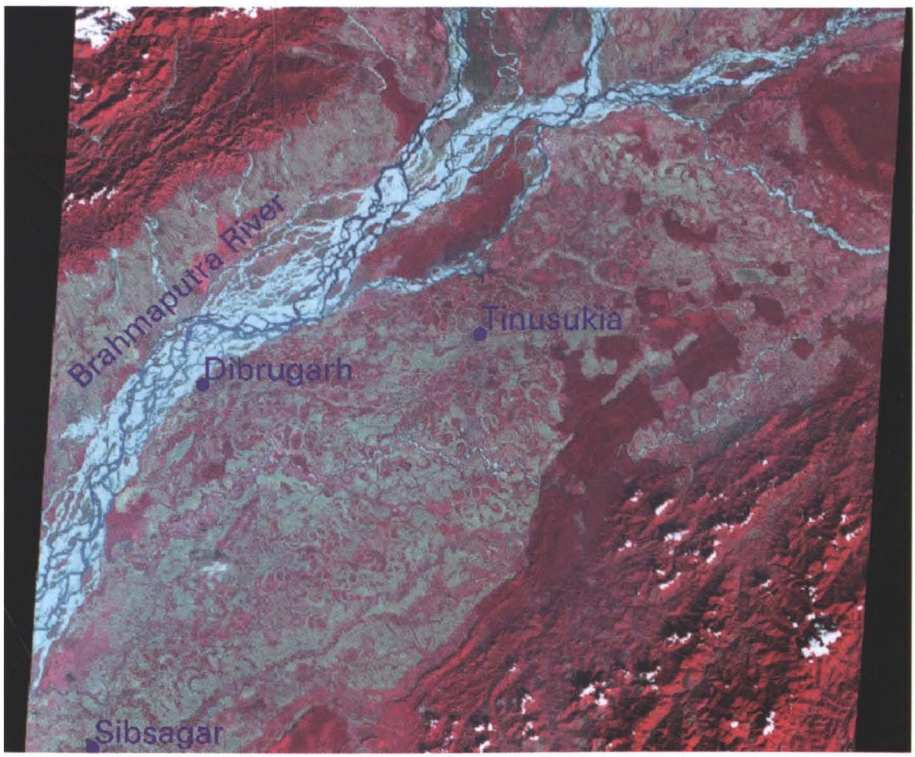
Shelly limestone in Ariyalur Group in Trichinopoly Cretaceous near Garudamangalam (Courtesy: S. Balakrishnan).

Obstacle miliolite deposit at Gop Hill, northeast of Porbandar in Saurashtra, Gujarat (Courtesy: N.P. Bhatt).



Satellite imagery of a part of Garhwal Sub-Himalaya and the Piedmont zone. Note the geomorphological expression of different tectono-stratigraphic units in the Dehra Dun region. The Lesser Himalaya to the north is constituted of Late Proterozoic to Early Cambrian Krol-Tal Formations. The hills to the south are made up of Middle (sandstones and mudstones) and Upper (Boulder Conglomerate) Siwalik Formations (Courtesy: A.K. Pandey).

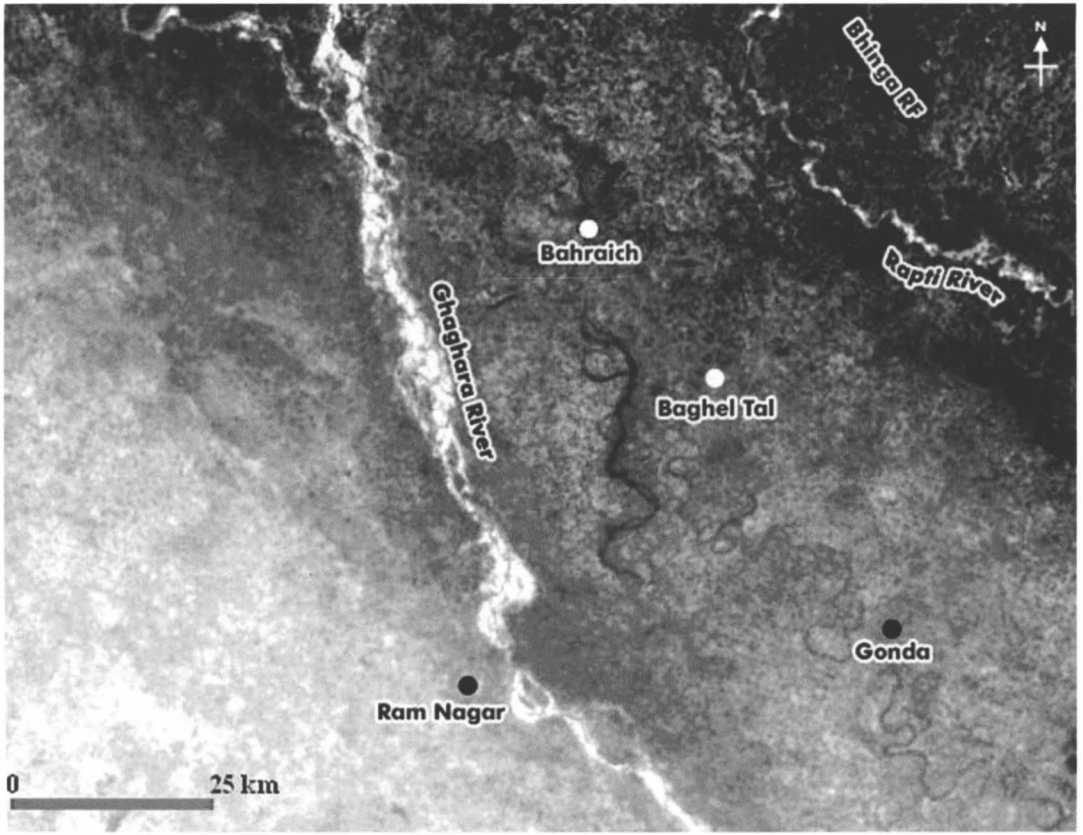
The hills are those of Lesser Himalaya with an average of ~1800 m height and gentle slopes of Siwalik Hills ~100 m average height. Further south the Siwaliks are buried under the Dun gravels (Courtesy: A.K. Pandey).



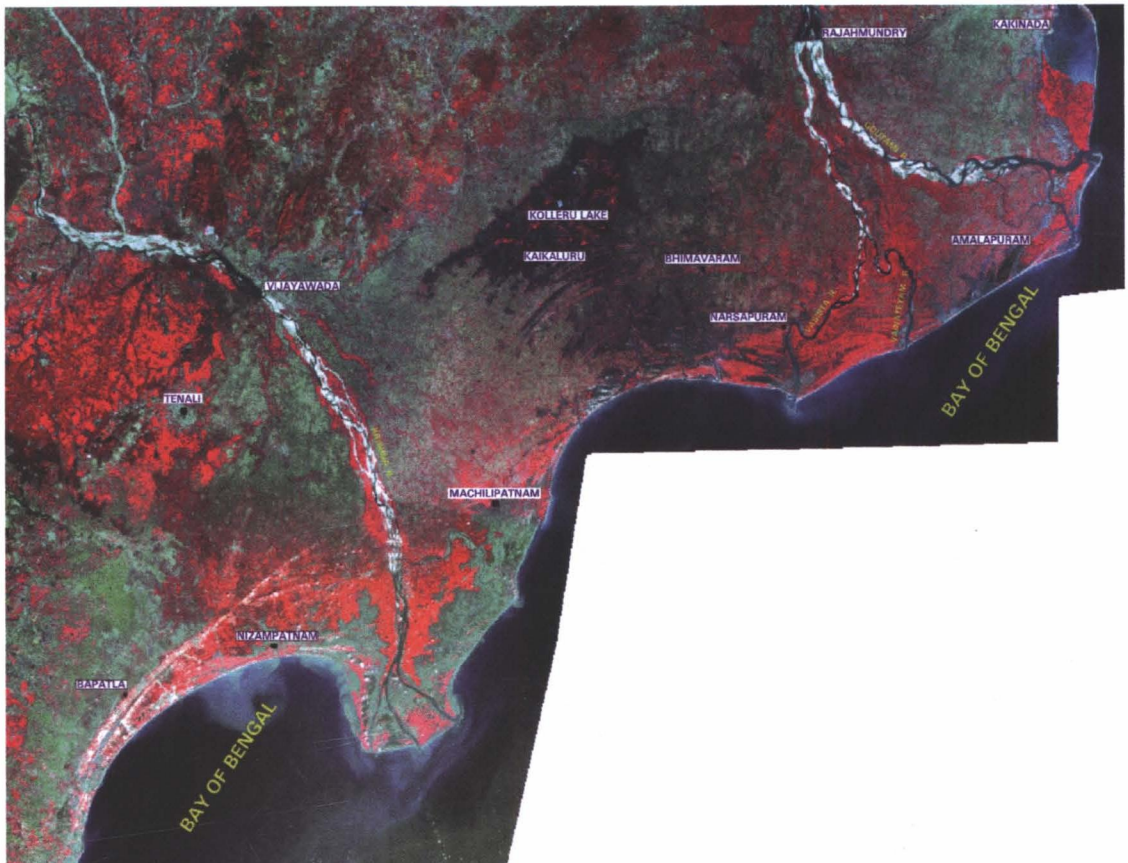
Satellite imagery of Brahmaputra Plain with the large river island of Majuli, NW of Tinsukia, along with numerous channels and tributaries of the river. Main Boundary Fault extending NE-SW is north of the river and the Naga Thrust extending NE-SW is southest of Tinsukia (Courtesy: G.Ch. Chenniah)

Flat-lying fluvio-lacustrine Quaternary Karewa sediments near Pompore in central Kashmir Valley (Courtesy: R.K. Mazari).

Section of Karewa sediments in Kashmir near Humhom, 10 km west of Srinagar City across the Jhelum River. Lacustrine strata of Nagum Formation of B is overlain by aeolian loess of Dilpur Formation. Hammer in B indicates scale (Courtesy: R.K. Mazari).



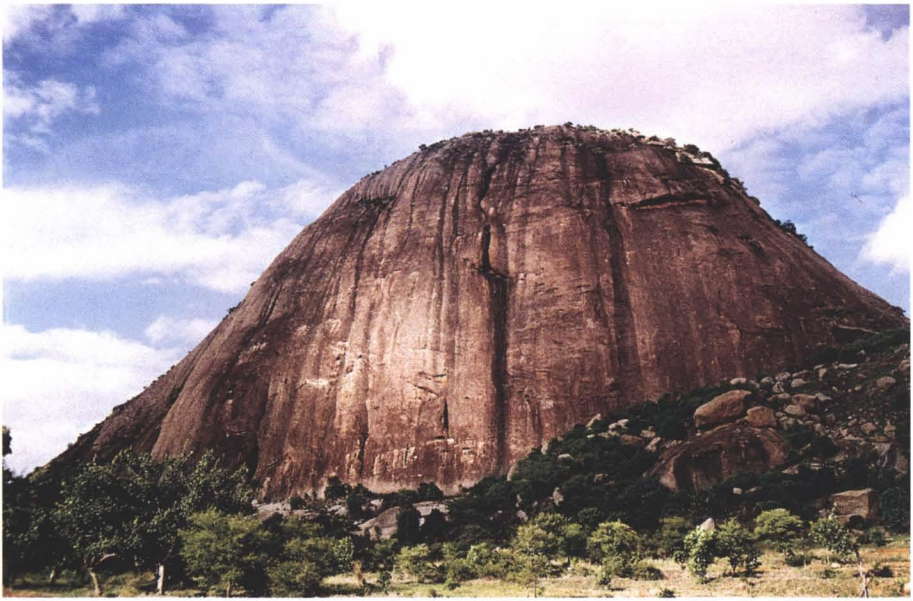
Satellite imagery of Ghagar Plain (in Indo-Gangetic Plain) showing numerous abandoned channels, oxbows and cut-offs typical of a flood plain (Courtesy: V.K. Jha).



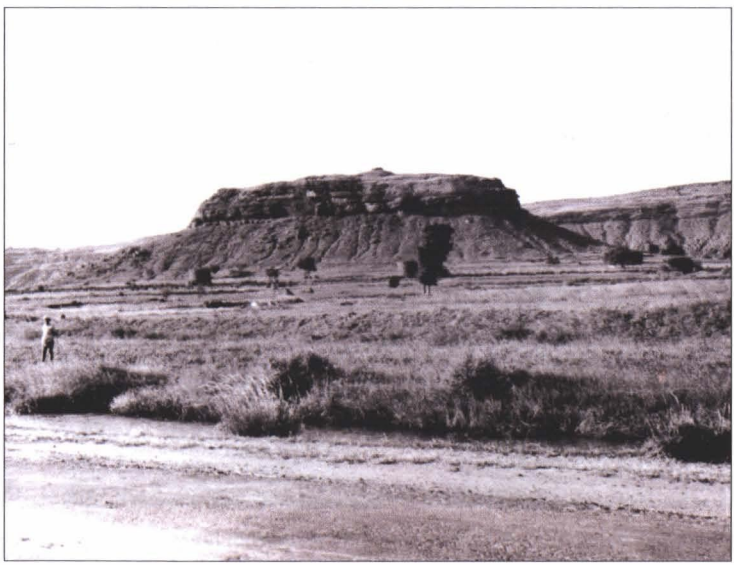
Delta plain of Krishna-Godavari, showing distributaries, ancient beach ridges and Kolleru Lake (Courtesy: GSI, Hyderabad).

Paired terraces of the river Chherup, a tributary of the Zanskar river overlain by a mound of mass movement deposit of periglacial origin (Courtesy: Milap Chandra Sharma)

Stalactites and stalagmites in Borra caves in Precambrian limestones near Anantagiri, Visakhapatnam district, Andhra Pradesh. Scale in feet (Courtesy: K.L.V. Ramana Rao)



Bornhardt (exfoliated granitic dome) – Handigandi rock, near Ramanagaram, Karnataka
(Courtesy: Mahadev)

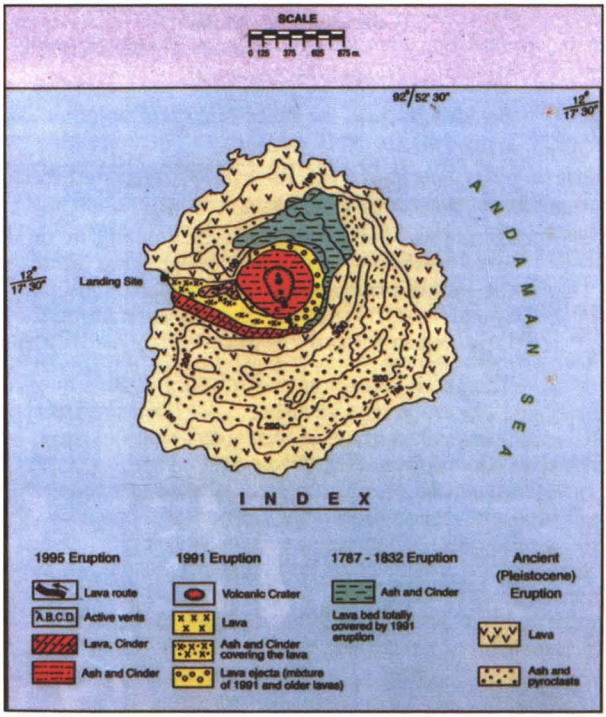


Mesa, flat-lying Badami sediments of Proterozoic over Archaean basement at Gajendragad, North Karnataka

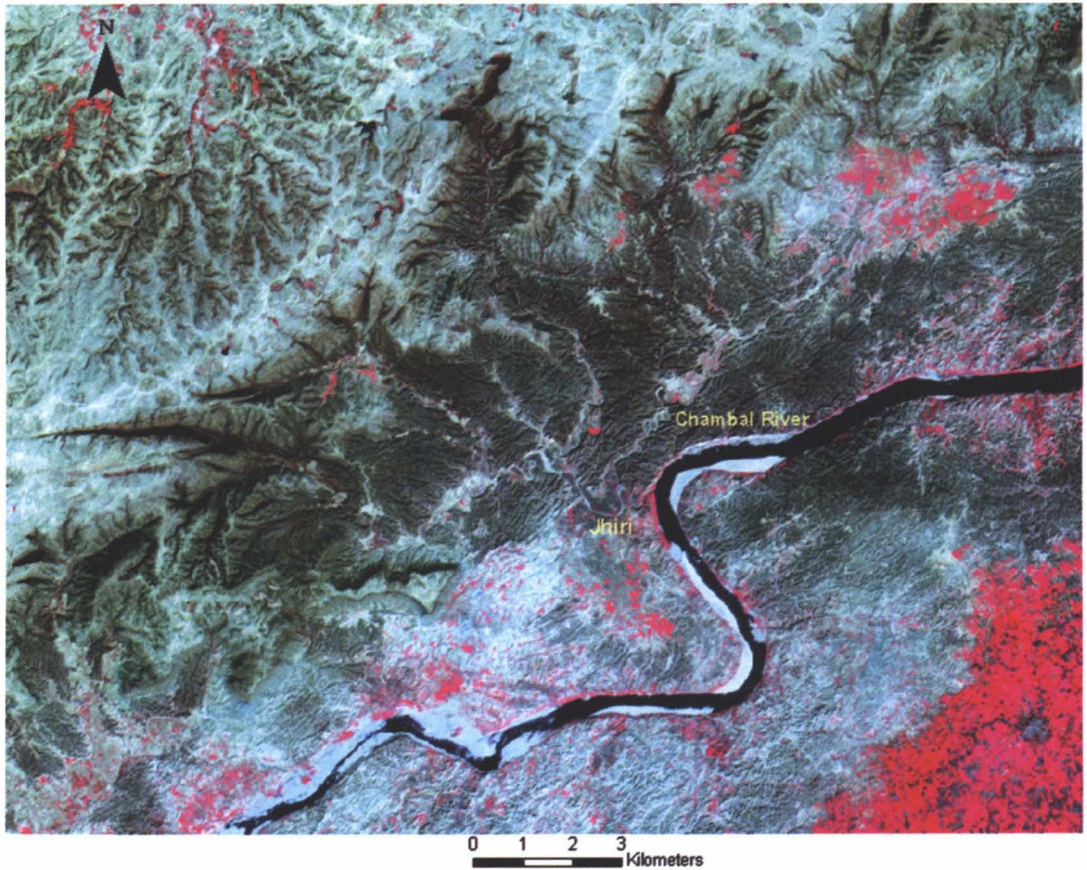
Step-like weathered argillites in the wave-cut platform near Port Blair, Andaman island (Courtesy: P.M. Mohan)

Shoulder of a 7 m high collapsed cave, above the present wave-cut abrasion platform near Gangavaram, south of Visakhapatnam in Andhra Pradesh (Courtesy: K.N. Prudhvi Raju)

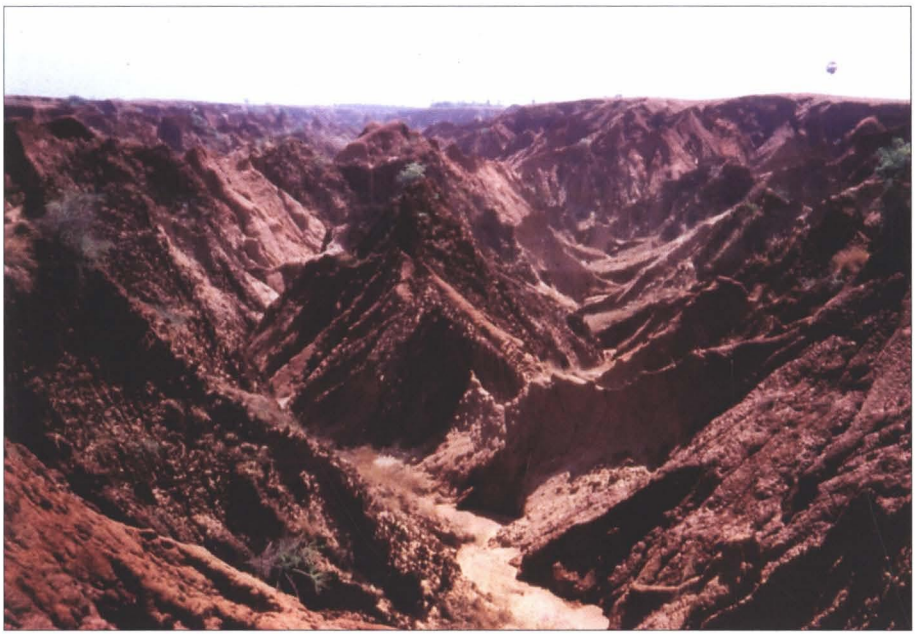
The climacteric stage of eruption of Barren Island volcano on 25th September 1991. Dark gas and white fumes gush out from the crater zone up to a height of more than 3 km. The fire fountains rise up to a height of about a km. (Ravi Shanker et al. 2001, Fig. 2.19, p.32).



Disposition of lava flow of Barren Island volcano, Andaman Sea, India (Ravi Shanker et al. 2001, Fig. 4.3, p.75)



Ravines around Jhiri on the border of Madhya Pradesh and Rajasthan, northwest of Chambal river (IRS LISS-III FCC, Dec. 2002; Courtesy: RRSSC, Nagpur)



Badlands 3-4 km southwest of Bhimunipatnam, close to the coast in Visakhapatnam district, Andhra Pradesh. The depth of the gullies in the foreground is about 13 to 15 m (Courtesy: K.N. Prudhvi Raju).

Barchan sand dunes in Western Rajasthan (Courtesy: H.S. Sharma).

THE BALDOTA GROUP

Adding Value to Nature's Resources

Founded by Late Shri Abheraj H. Baldota in 1961, the Baldota Group is one of India's leading iron ore mining companies and holds the distinction of being one of the largest producer of wind power in the country.

Under his visionary aegis, the Baldota Group transformed from a fledgling mining company to a full-fledged conglomerate, achieving leadership position in diversified businesses such as Iron Ore, Wind Power, Gases, Steel, Shipping, Chemical and Diamond & Gold Exploration. The Group has also demonstrated unflinching commitment to the community and has been recognized for its environment stewardship through various national awards.

IRON ORE MINING

Breaking New Grounds

MSPL Limited, a flagship company of the Baldota Group, is the largest exporters of iron ore from the private sector. MSPL has won the CAPEXIL Export Award consequently for seven years for its excellent export performance.

The Group is also foraying into diamond and gold exploration in the states of Karnataka and Andhra Pradesh and is likely to initiate exploration of base metals, REE and Potash in Rajasthan.

WIND POWER

Empowering a Greener Future

The Baldota Group, through MSPL and its group companies diversified into Wind Power generation. Its wind farms across Karnataka, Maharashtra, Rajasthan and Gujarat have a total group capacity of 215.75 MW, which is the largest installed wind power capacity in India.

MSPL's Wind Energy Project has been registered as one of the largest renewable energy CDM projects in the world by UNFCCC.

GASES

Leadership through Service

MSPL Gases undertakes the medical and industrial gases business of the Baldota Group. It manufactures gases like liquid and gaseous oxygen, nitrogen, and argon gas. Recently, it commissioned the first Air Separation Plant for the Indian Railways on a Build, Own, Operate and Transfer (BOOT) basis.

STEEL

Proving its Mettle

The Baldota Group is setting up an advanced integrated steel plant in Karnataka - Aaress Iron & Steel Limited. This project will initially set up a 2.5 MMT steel production capacity per annum and a 180 MW power plant to generate power by using waste heats from the process.

The Baldota Group is riding on the crest of some eventful years. It was honoured with the First Prize for Independent Power Producer under Wind Programme (2002-07) by the Ministry of New and Renewable Energy. In 2006 it was awarded the prestigious CFBP (Council for Fair Business Practices) Jamnalal Bajaj Award for Fair Business Practices and the Export Excellence Award by the Federation for Karnataka Chambers of Commerce and Industry (FKCCI) for its outstanding export performance. In 2009, the Indian Wind Power Association (IWPA) accorded MSPL with the "Best Performing Wind Farm" award (above 2 MW category) among all wind farms in Karnataka and Andhra Pradesh.

BALDOTA

BALDOTA GROUP

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About Authors

Prof. R.Vaidyanadhan was born in 1931. He obtained his Master's and Doctoral degrees from the Geology Department, Andhra University, Visakhapatnam and was a faculty member from 1953 and retired as Professor in 1991. He had his training in Geomorphology and Photo-interpretation in the Geology Department and the Institute of Cartography, Geodesy and Photogrammetry respectively at the Ohio State University, Columbus, Ohio, USA and in Photogeology at the United States Geological Survey, Washington, D.C. He served as a Professor in Geology at the University of Dar-es-Salam, Tanzania for two academic years during 1981-83. He has conducted training programmes in geomorphological mapping for students and professional geologists sponsored by the Department of Science and Technology and the Geological Survey of India respectively. He has published over 70 papers and supervised 12 students for Ph.D. degree at the Andhra University. A majority of the papers are in the fields of Quaternary Geology, Geomorphology and Remote Sensing. He has carried out projects funded by UGC, CSIR, ONGC, DST, ISRO, Ministry of Defence, Planning Commission etc. during 1965-1991. He was the Editor of the Journal of the Geological Society of India, Bangalore for a term during 1992-1995 and was a Vice President of the Society during 1998-2004.

Dr.M.Ramakrishnan is an outstanding Precambrian Geologist who has specialized in the geology of southern India. He was born in Madurai, Tamil Nadu in 1940. He did M.Sc from the Presidency College, Chennai (1962) and obtained Ph.D from the Indian Institute of Science, Bangalore (1981). He retired as Senior Deputy Director-General of the Geological Survey of India (1998). He also headed the Centre for the Earth Science Studies, Thiruvananthapuram (1987-89). He served as Scientific Board Member of the International Geological Correlation Programme (IGCP) of the UNESCO, Paris (1992-1997), and several committees of the Department of Science and Technology, Department of Atomic Energy, Space Applications Centre and other Government Departments, Indian Institute of Technology and many other geoscientific societies, national institutes and universities. He served the Geological Society of India in various capacities including the Editor (1998-2001) and Vice President (2201-2004) under his mentor Dr.B.P.Radhakrishna. He was awarded the Mysore Geologists' Gold Medal (1984), the National Mineral Award of the Government of India (1989-90) and Golden Jubilee Honour of the Geological Society of India (2008) and Life Time Achievement Award of the South Asian Association of Economic Geologists (SAAEG) in 2008.

Field geology has been his forte as evidenced from his extensively cited publications on Dharwar and Chhattisgarh geology, Eastern Ghats and Pandyan mobile belts and 'Purana' basins. M.N.Viswanatha, J.Swami Nath and B.Chadwick were his main field companions. He has participated in numerous field geological excursions and travelled widely in India and abroad. He has worked in the classical high-grade terrain of West Greenland with Prof.B.Chadwick of Exeter University, U.K. He has collaborated with well-known Precambrian geologists like S.Moorbath, B.F.Windley, A.Kroner, B.Chadwick, A.Nutman and B.P.Radhakrishna. He has compiled several thematic geological maps, published numerous scientific papers and edited valuable books on regional geology. He has also served on the editorial boards of many prestigious earth science journals.